Grain Storage,
Moisture, Rodents,
microflora, Grain Drying,
Insect pests,
flour Storage.
Cereal Packaging.

STORAGE
of Cereal Grains and Their Products

AMERICAN ASSOCIATION OF CEREAL CHEMISTS

Monograph Series ***Volume II***

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STORAGE
of Cereal Grains and Their Products

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Preface

Storage of Cereal Grains and Their Products is the second in a series of monographs sponsored by the American Association of Cereal Chemists. The subject seems especially timely; for in spite of recent advances in technology, millions of tons of cereals are wasted each year through spoilage of various sorts. Yet hunger is widespread, and populations increase ever more rapidly. Protection of food supplies through sound storage practices is thus a matter of the most vital importance.

Each of the eleven chapters of the book has been written by one or more experts. The chief aim was to produce a useful treatise by combining comprehensive reviews of the scientific literature with knowledge drawn from other sources. In pursuit of that aim some unevenness among chapters could not be avoided; for some aspects of the subject are brightly illuminated by the light of scientific knowledge; on others that light is dim, and we must depend largely on practical experience; and elsewhere, even practical experience is limited, and we grope in semi-darkness.

The first six chapters deal with moisture, chemical and physical changes with time, microflora, respiration and heating, insects, and rodents. Their main purpose is to provide the scientific background for a consideration of storage problems, though all, and especially those on insects and rodents, do full justice to practical matters also. The last five chapters, by contrast, deal largely with areas in which practical experience is the chief source of knowledge. Two describe grain storage facilities in the country and at terminal points, and discuss their operation; one deals with grain drying; and the last two with cereal products themselves, namely, with bulk storage of flour and with packaging of various types.

Three further comments may appropriately be made on the book as a whole. Firstly, since authors were urged to deal fully with their subjects it was inevtitable that some topics should be discussed in more than one chapter. We did not attempt to remove all such repetition since we believed that the reader would prefer to have each chapter essentially complete in itself. Secondly, while the treatment is often both comprehensive and detailed, not all cereals and their products are fully covered. The aim was primarily to elucidate and illustrate the main principles governing storage rather than to discuss specific problems presented by

individual grains or products. And lastly, as might be expected, since all authors—and the editors—are citizens of the United States or Canada, the book gives most emphasis to North American investigations and practices.

We are deeply indebted to our authors for the time and labor they gave to the preparation of their chapters, and for their patience, forbearance, and cooperation, in dealing with the many matters, some important and some trivial, that authors and editors are bound to discuss. Circumstances beyond our control made it necessary to find a number of new authors when about half the book had been written, and as a result, the completion of the work was considerably delayed. We are therefore especially grateful to those authors who turned manuscripts in early and were later kind enough to bring them up to date; and to those who, coming to their tasks late in the day, made special efforts to meet our postponed deadlines.

In carrying out our part in the preparation of this book we received much help and valuable advice from the chairman of the Monograph Committee, W. F. Geddes. The other members of this committee were C. N. Frey, George Garnatz, Majel M. MacMasters, Betty Sullivan, J. A. Shellenberger, and ourselves. The committee chose the subject for the book, prepared an outline of its contents, selected authors for the various chapters, and asked them to contribute.

We were particularly fortunate in persuading Kathleen Webb, who helped with Volume I of this series, to undertake the technical editing of Volume II also; her painstaking work has added immeasurably to the quality of this book. Eunice R. Brown, Margaret Hilligan, V. G. Martens, and R. J. Cheale also gave us valuable assistance. Lastly, we pay a well-earned tribute to R. J. Tarleton, Managing Editor of *Cereal Chemistry*, who undertook the final work of publishing the book for the American Association of Cereal Chemists.

J.A.A.
A.W.A.

October, 1953.

Contents

CHAPTER I

Moisture and Its Measurement

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In order to understand the role of water in cereal grains as related to the problems of storage, it is necessary to consider first the underlying principles involved when water is absorbed by the various substances of the grain. Only when such principles are clearly understood is it possible to appreciate the full scope of the more practical aspects of the relation of water to grain storage; for principles are the unifying concepts that transform seemingly unrelated data and experience into the systematized knowledge called science. A discussion of these basic considerations is therefore presented in the first section of this chapter. The second section describes and compares methods used for determining the moisture content of cereals. These methods are essentially empirical and can yield accurate results only when calibrated in terms of some basic reference method. Accordingly, the search for a method that will yield the "true" moisture content of cereal grains is continuing; research in this field is reviewed in the third and final section of the chapter.

Basic Considerations

As a starting point we may inquire into what is known about the forces that hold water in biocolloid systems such as grain, whether these forces are chemical or physical, how strong they are, what chemical groups are responsible for binding water, and so on. This leads to a discussion of adsorption in relation to chemical structure and thence to a consideration of what may be learned from water sorption isotherms. Information on isotherms for cereals and their products is then presented, and the section ends with a discussion of the concept of "bound water."

Forces Involved in Adsorption. First let us examine in what ways water may be held by substances which absorb it. For purposes of the present discussion, it is convenient to consider water absorption as several distinct phenomena. A certain amount of water may be held in the inter-

granular spaces and within the pores of the material. Such water may be termed free water, i.e., it possesses its usual properties, and the molecules of the absorbing substance are not concerned except as a supporting structure.

Another portion of the water is more closely associated with the absorbing substance. There is an interaction between the water molecules and those of the substance; in other words, the properties of one substance influence the properties of the other. Water is then said to be adsorbed. The general term sorption is used to denote such interaction, while adsorption and desorption are used specifically to denote the processes of taking up and giving off water of sorption.

Finally, some water may combine in a chemical union with the absorbing substance; and conversely, water which is an integral part of a given substance may be removed under rigorous conditions at times employed for moisture determination.

The foregoing classification must be regarded merely as the setting up of useful categories. It must be kept in mind, however, that in a biocolloid system, such as grain, which is made up of various substances and which also possesses an organized structure, there will be present a whole spectrum of types of water binding, ranging from free water to chemically bound water that forms an integral part of some organic molecule. For the purpose of the present exposition the most pertinent inquiry is in that somewhat indefinite area between free water that remains uninfluenced by the grain, on the one hand, and water which is chemically combined, on the other, an area in which intermolecular forces play a dominant role. It is therefore necessary to examine what these intermolecular forces are.

When atoms unite to form molecules, all the chemical bonds are satisfied, but the molecules can still exert influence on other molecules by means of forces variously termed as intermolecular forces, van der Waals', and secondary valence forces (18, 52). These manifest themselves in the formation of liquids and crystals, of complexes and aggregates, and in other types of interaction between molecules of the same or different kind.

The origin of intermolecular forces has been attributed to several effects (18, 52). The first of these is the orientation effect of permanent dipoles, sometimes called the Keesom effect, which may be described as follows. If by reason of the structure of a molecule the center of gravity of positive charges does not coincide with the center of gravity of negative charges, that molecule is said to possess a permanent dipole moment. Water, alcohol, and ammonia are good examples of substances with dipole moments. When two such molecules approach each other there

will be an electrostatic attraction between the positive end of one molecule and the negative end of the other.

A second effect is called the induction effect of Debye. When molecules which contain easily mobile charges are brought near a strong dipole or ion, or are placed in an electric field, a distortion of the negative charge clouds surrounding the atoms takes place. As a result, the centers of gravity of negative and positive charges in the molecule will no longer coincide and the molecule is said to acquire an induced dipole moment. This process is broadly analogous to the induction of magnetic polarity in a piece of soft iron in the presence of a permanent magnet. Interaction between the inducing dipole and induced dipole gives rise to a force of attraction.

A third type of interaction between molecules is the London dispersion effect. This is also an attractive force; the term dispersion is derived from certain optical properties. As an example, consider an atom of hydrogen which is generally thought to be nonpolar. Its dipole moment, however, is zero only statistically over a finite interval of time. But at any instant, the single electron of the hydrogen atom is always on one side so that the atom possesses a dipole moment constantly fluctuating in direction. This will create a fluctuating field around the atom and will result in a displacement of charge in a nearby atom in phase with the fluctuation. This type of interaction then gives rise to a force of attraction.

Usually, the attraction between molecules will not be a simple effect but rather the combined effect of several kinds of interaction. There may be dipole-dipole, dipole-induced dipole, ion-dipole, etc., interaction. For example, the binding of water to the copper ion in the pentahydrate of copper sulfate is an ion-dipole interaction. The hydrogen bond deserves special mention. It may be visualized as consisting of a hydrogen atom forming a bridge between two electronegative atoms or groups. The dipole forces and quantum mechanical resonance cooperate to form a stable link.

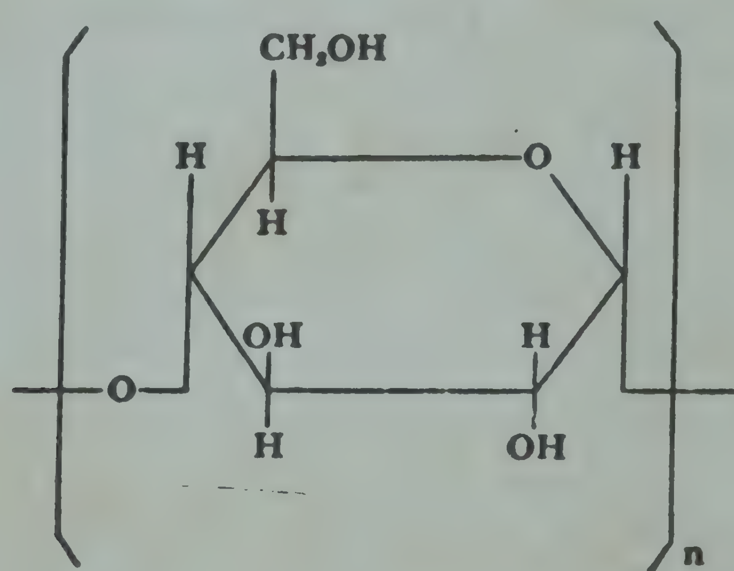
Intermolecular forces are relatively weak. The heat of adsorption of one substance on to the surface of another may range from 4 to 15 kcal. per mole. When the energy involved is from 15 to 35, or even up to 50 kcal. per mole, the process is sometimes termed chemisorption to indicate that it is intermediate between sorption and chemical binding by means of covalent or ionic bonds. The latter type of bond may involve 50 to 150 kcal. or more.

Water occupies a prominent position in adsorption phenomena. It has already been pointed out that water has a permanent dipole. In addition, it is a small molecule and therefore has a large dipole moment per unit

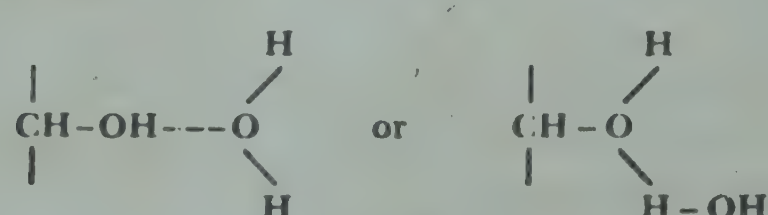
surface. Water would thus be expected to be strongly adsorbed on polar substances, and especially so on substances containing ions.

Adsorption and Chemical Structure. It is logical to inquire next to what extent intermolecular forces may be expected to be involved in the process of sorption of water by cereal grains. To do this, it is necessary to note briefly the significant structural characteristics of the predominant constituent substances occurring in grain, and to identify the polar foci or functional groups which govern the behavior of these substances towards water. Starch and protein have been selected for a brief discussion.

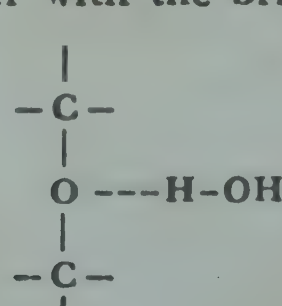
Starch is a natural high polymer built up from the basic glucose unit by repetition into a long or branched chain. It may be represented by the formula:



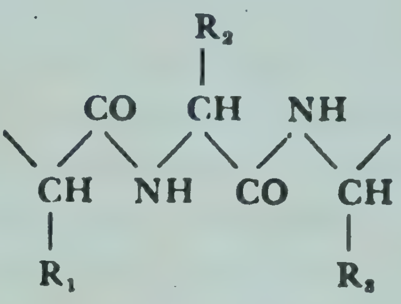
It is characterized by hydroxyl groups on the ring, ring oxygen, and bridge oxygen, all of which are points of polarity in the molecule and therefore suitable foci for interaction with water molecules. Hunter (42) suggests the following modes of linkage of the polysaccharide hydroxyl with water, through a hydrogen bond:



For the interaction of water with the bridge oxygen he suggests:

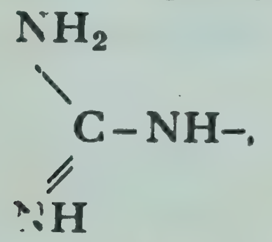


The structure of protein is also that of a high polymer, but the repeating unit is not identical and may be any of the naturally occurring amino acids. One of the most significant structural characteristics of protein is the polypeptide backbone:



R_1, R_2, etc., are the amino acid side chain residues. They carry a wide variety of polar and ionic groups:

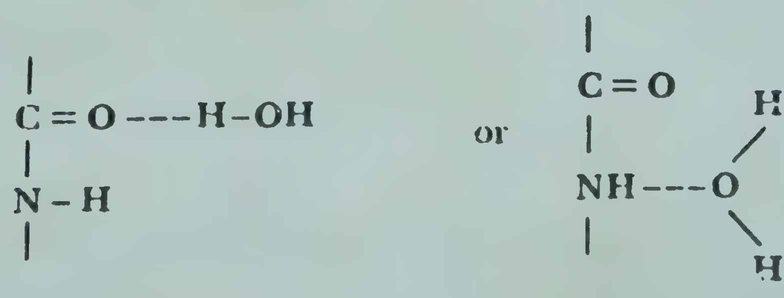
–OH , in serine, threonine, hydroxyproline, and tyrosine;
–NH– , in tryptophane, histidine, and proline;
$–NH_2$, in lysine and in one of the terminal amino acids in the polypeptide chain;

 , in arginine;

–COOH, in aspartic and glutamic acids and in one of the terminal amino acids in the polypeptide chain; and
$–CONH_2$, in glutamine and asparagine.

Accordingly, there is ample opportunity for water to interact with a variety of polar groups.

This approach to the problem of binding of water has been adopted by several investigators. Lloyd (48) recognized the multipolar character of proteins and pointed out the possibilities of various groups coordinating with water. Pauling (65) also concluded that water adsorbed in the first layer by proteins was bound primarily by the polar side chains. He attached less importance to the effect of the peptide link. Hunter (42), however, suggested that water is bound by the peptide link according to the scheme:



Sponsler, Bath, and Ellis (86) give an interesting estimate of the amount

of water which may be held by various groups in proteins. The carboxyl group can coordinate or bind 4 to 5 molecules of water; amino group, 3 molecules; hydroxyl group, 3 molecules; imino and carbonyl groups, 2 molecules each. More recently, Mellon, Korn, and Hoover (55, 57) determined the extent to which the amino and the peptide groups in proteins participate in binding water. For casein, they concluded that 24 to 33% of the total water adsorbed was held by the amino groups and an additional 45% by the peptide linkages. In zein, the peptide linkage adsorbed 70% of the total water taken up at a relative humidity of 80%. Further fundamental studies of this type are required.

The Water Sorption Isotherm. A very useful approach to the study of the adsorption of water by solid substances, such as those occurring in cereal grains, is by means of the isotherm. An isotherm is simply a curve describing the equilibrium relationship, at a specified temperature, of the amount of water sorbed by the substance, on the one hand, and vapor pressure or relative humidity, on the other. Depending on whether water is taken on or given off by the solid in approaching an equilibrium between vapor pressure and moisture content, the isotherm may be an adsorption or a desorption isotherm.

In general, the isotherm may be described as an S-shaped curve such as that shown for flour in Figure 1. In the low humidity range it is concave to the humidity axis; in the mid range, the isotherm has a region of inflection which is approximately linear; and in the high humidity

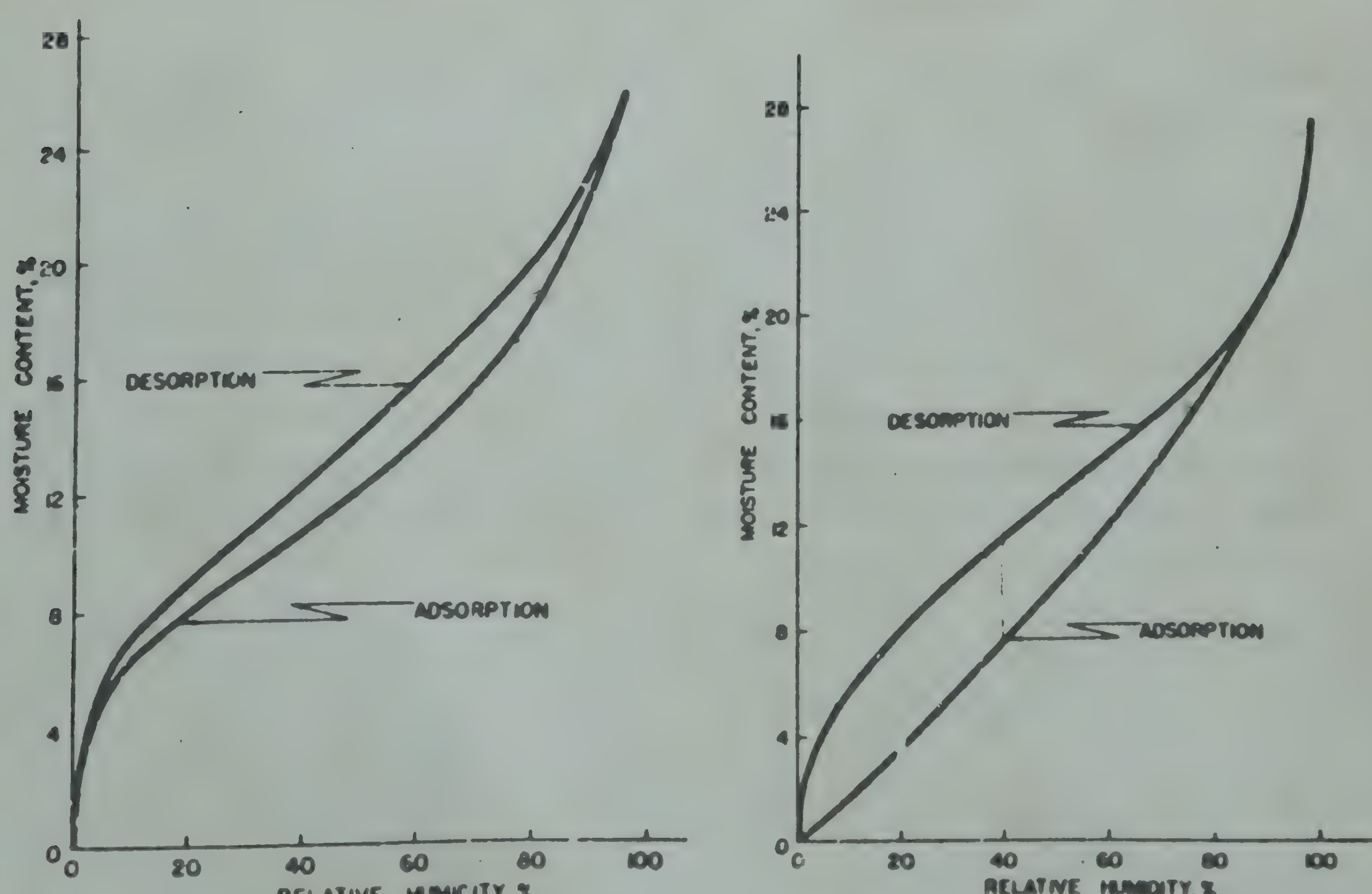


Fig. 1. Left, isotherms for flour at 25°C.; right, isotherms for wheat at 25°C. (7)

range it is concave to the moisture content axis. The S-shaped isotherm is characteristic of cellulose (80) and of proteins, e.g., casein (56) and edestin (37). The S-shape is also common to numerous other materials including cereal grains and their products. The shape of the isotherm is significant and its implications merit discussion in greater detail.

According to the Brunauer-Emmett-Teller theory of multilayer adsorption (19), the first portion of the isotherm represents the adsorption of the first layer of water vapor on to the surface of the adsorbing material: the region of inflection represents the deposition of a second layer of water molecules; and the final curved portion represents the continued adsorption of additional layers. In polar substances such as proteins, adsorption may first take place on specific sites, as has been pointed out in the preceding section, and a suitable modification of the theory has been made to apply to what is termed active adsorption (20). The initial portion of the isotherm may thus include only the deposition of water on polar sites, while the region of inflection includes the deposition of a first layer on nonpolar sites as well as of an entire second layer. An alternate hypothesis that water is adsorbed at polar sites as clusters of molecules rather than in layers has also been suggested (88). For a more detailed discussion of various theories of sorption of water by proteins and polymers, the reader is referred to a recent review by McLaren and Rowen (54).

In each of the three segments of the isotherm a different relationship between vapor pressure and moisture content governs. In the initial portion of the isotherm, the vapor pressure-moisture content relationship is governed by the energy of binding between the water molecules and the adsorbing surface. The binding energy depends on the physical structure of the surface and its chemical constitution, and on the physical and chemical properties of water. The magnitude of the binding energy will thus be the resultant of various effects. The extent to which the isotherm is displaced towards the moisture-content axis is an indication of the binding energy between water and the adsorbing substance.

In the intermediate almost linear portion of the isotherm, water molecules are being deposited on the water molecules already present in the first layer, and to a smaller extent on the nonpolar sites which have little influence on the properties of water. The energy concerned in this process is predominantly that of condensation of water. In this range the amount of adsorption is strongly dependent on the water vapor pressure.

In the high humidity range the vapor pressure is determined primarily by the second layer which already covers the entire surface. Addition of third, fourth, and successive layers appears to be a kind of capillary

condensation. The water in each layer deposited possesses nearly the same properties as water in the preceding layer. Thus, the amount of water sorbed increases very rapidly in this range, but the vapor pressure of the system is influenced only moderately.

The most interesting part of the isotherm is the initial portion, for it is generally considered to describe the forces of interaction between grain constituents and water. The strong displacement of this part of the isotherm towards the moisture-content axis is interpreted as indicating that strong intermolecular forces and perhaps chemisorption are involved in the adsorption of water by the grain at low vapor pressures. Something of the magnitude of the forces involved is indicated, for example, by Babbitt's observation (7) that 3% moisture was retained by wheat and 0.8% by flour even in systems evacuated with a mercury diffusion pump. Heats of hydration for flour, gluten, and starch, which are also indicative of the binding energy, have been measured by Winkler and Geddes (92) and by Schrenk, Andrews, and King (79). Values of 27 calories for flour and 20 calories for gluten were obtained when 1 g. of these moisture-free substances was added to a large quantity of water. These values however are average heats of hydration. More informative data would be obtained by adding 1 g. of water to a large quantity of the dry substances. A value of 260 calories is reported (37) when a large amount of moisture-free casein takes up 1 g. of water. Data of this kind for cereal products are necessary in order to describe more clearly the mechanism of binding between water and the adsorbing substances in the grain.

Hysteresis. The adsorption and desorption isotherms for a given substance are not necessarily the same. In fact, with many substances, including cereals and their products, the desorption isotherm is markedly displaced to the left of the adsorption isotherm. Figure 1 shows adsorption and desorption isotherms for wheat. The curves show that different samples of the same grain in equilibrium with the same atmosphere do not necessarily have the same moisture content; in fact the differences appear to be surprisingly large. This influence of the direction from which equilibrium is approached – or, in general, the previous history or treatment of the sample – is known as hysteresis effect.

Both chemical and physical factors have been advanced in various hypotheses to account for the phenomenon of hysteresis. Zsigmondy (93) and McBain (53) considered that capillary phenomena were the dominant factors in hysteresis. The influence of structure of cereal grains and their products can be inferred from the observation (7) that hysteresis is not as pronounced with flour as with whole wheat. Swelling that results from the absorption of water by a gel system may also be associated with structure; its importance has been stressed by Urquhart (90) and Smith

(81). Pierce and Smith (67) point out that plane surfaces with no capillary structure may also show hysteresis. They suggest that hysteresis results from the energy changes which take place in the system when water, deposited first as clumps at active centers, merges to form a layer covering the adsorbing surface. Recent work of Benson, Ellis, and Zwanzig (10) shows that adsorption of water on proteins may be blocked by other substances such as oxygen of the air. They showed that, in the absence of oxygen, adsorption and desorption equilibria could be reached in 1 to 3 hours. In comparison, previous work showed that, in the presence of oxygen, 6 to 8 days were required for adsorption and over 18 days for desorption equilibrium to be attained. Thus several factors may be involved in the hysteresis effect; in materials such as cereal grains, which possess an organized structure and which are made up of widely different substances, a multiple effect can indeed be expected.

Isotherms for Cereals and Their Products. So far, the discussion has been focused on the theoretical principles considered basic to an understanding of problems concerned with moisture in cereal grains and their products. In this section attention will be given to a brief survey of the progress which has been made in the study of the properties of various cereal grains and their products in relation to water sorption.

A classical study of the water vapor sorption isotherms of cereals is that of Coleman and Fellows (25). They equilibrated various grains with atmospheres of known relative humidity. In addition to wheat of various types, corn, oats, barley, rye, rice, buckwheat, and flaxseed were also studied. In general, the moisture contents of all cereals in equilibrium with the same relative humidity were much the same, except that flax had a much lower moisture content. This, no doubt, results from the high oil content of flax. Comparable results might be expected if the data were expressed on a fat-free basis. Oxley (63, 64) summarized the results of similar studies by several prominent investigators. Babbitt (6, 7) was among the first to differentiate clearly between adsorption and desorption equilibria. In his isotherms for wheat, redrawn in Figure 1 (right), the large difference between the adsorption and desorption isotherms is the hysteresis effect discussed in the previous section.

Adsorption isotherms for flour have been obtained by Bailey (8), Fairbrother (32), Anderson (4), Anker, Geddes, and Bailey (5), and also by Babbitt (7). Knight and Larmour (47) obtained isotherms for flour, bran, shorts, screenings, and middlings. It will be observed, by comparison of the isotherms in Figure 1 (reproduced from Babbitt), that the hysteresis effect for flour is smaller than that for whole wheat.

Morey, Kilmer, and Selman (59) studied the equilibria between moisture content and vapor pressure for flour over a temperature range

of 50° to 90°C. The relation between temperature and the logarithm of vapor pressure at a specified moisture content is essentially linear and may be expressed mathematically as

$$t = a \log p + b$$

where t is temperature, p vapor pressure, and a and b are constants. Morey *et al.* showed that vapor pressure increased markedly with temperature. When, however, vapor pressure is expressed as relative humidity, the function is quite insensitive, and for moderate ranges of temperature, relative humidity is often assumed to be independent of temperature.

Similar data on sunflowerseed and oats (26), on rice (43), and on starch (38, 39, 77) and other related data may be found in the literature.

The foregoing account shows that much preliminary information as well as information of practical value has been obtained. However, the investigations varied widely in their experimental technic and materials used, so that much of the work is not strictly comparable. Some of the work is restricted to limited ranges of relative humidity. Many workers failed to appreciate the distinction between adsorption and desorption, and the magnitude of the hysteresis effect. Moreover, most of the work antedated the significant development of the theory of multilayer adsorption and was thus limited in scope.

Interesting general inferences may be made from the isotherm studies. The isotherms for different grains and by-products are remarkably similar. This leads to the generalization that the same basic principles govern their water sorption properties. Further study of the sorption isotherms for wheat and flour (Fig. 1) will show that the initial portion of the isotherm corresponds to a water content of about 6%. The linear portion of the isotherm represents an additional 10% moisture content. These results are in accord with the theory of activated adsorption described in a preceding section. The first monomolecular layer of water is adsorbed on active centers only; the second layer is adsorbed on the surface not covered by the active centers, and on the first water layer. The amount of water adsorbed in the first portion of the isotherm would thus be expected to be less than that represented by the linear portion of the isotherm. The final curved portion of the isotherm begins at about 80% relative humidity. It represents the deposition of successive layers of water. At this point, then, relatively large amounts of water become available and may be utilized by the grain or by microorganisms. In practice, moisture contents in equilibrium with 75 to 80% relative humidity represent the level at which stored grain may be expected to deteriorate rapidly. These inferences are merely qualitative, but they indicate the direction which future research may well take.

Bound Water. Now that the forces involved in adsorption and the significance of isotherms have been discussed, the concept of so-called bound water may be briefly considered. The reader is also referred to a recent review by Makower (49) on this subject. Let us recapitulate some of the salient points already noted which are relevant to the discussion of bound water. The isotherm has been considered in three sections, the initial curved portion, the intermediate linear portion, and the final curved portion. It has been pointed out that the energy of binding involved in the last two sections of the isotherm is principally that of condensation of water. Accordingly, it is the initial portion of the isotherm that must be emphasized, since it is in this region that interaction between water and the adsorbing substance is involved. It has also been pointed out that adsorption of water on substances of which grain is composed takes place on specific active groups such as the carboxyl group, amino group, peptide linkage, hydroxyl, etc. There is thus no single type of binding but many types, each with a characteristic energy of reaction between water and the group on which adsorption takes place. The resultant of all these types of binding, ranging from inactive sorption to chemisorption, is represented by the isotherm. In other words, the isotherm represents "the normalization integral of the distribution function of site energies" (44).

The concept of bound water carries two implications. It implies that some water adsorbed by the grain, for example, is held by forces stronger than those of simple cohesion between water molecules themselves. From what has been said so far, such a view certainly appears justified. This concession, however, does not endorse the bound water concept in its historical sense. Traditionally, bound water also implies a quantitative stoichiometric relationship between water and the adsorbing substance. Numerous attempts have therefore been made to determine the amount of bound water and a variety of procedures has been developed.

It should be kept in mind, however, that the adsorption isotherm is a complete description of the water-binding relationship in the system and that any method which is used to determine "bound water" is one which more or less arbitrarily selects some point on this curve: water present and possessing a relative pressure above this point is called "free" while water adsorbed with a greater energy than that corresponding to this point is called "bound." The term "bound water" is thus relative, and the methods for the estimation of bound water are arbitrary.

The above condition is not analogous to hydrate systems containing water of crystallization in which the presence of a hydrate can be sharply distinguished by the vapor pressure of the system. Isotherm studies on the more complex biocolloid systems show clearly that no such point

of demarcation can be selected. A discontinuity or break in the isotherm would be required. Such a break can hardly be expected in isotherms of systems in which a multiplicity of types of water binding are involved. Even in more favorable instances, as with starch, in which the number of types of adsorption sites is small and an orderly latticelike arrangement occurs in the granules, the isotherm does not show a discontinuity—though Meyer (58) suggests that a hydrate $(C_6H_{10}O_5 \cdot H_2O)_n$ exists corresponding to a water content of 10%.

At the present time, bound water should probably be regarded as an indefinite concept. Or perhaps the meaning of the phrase "bound water" will shift, in line with newer developments in this field. Future quantitative studies of bound water will likely continue to be focused on adsorption energies at specific sorptive sites and on the energy contributions of various chemical groups. The older work has served well to emphasize the importance of and to lay the foundation for such studies.

Determination of Water Content

Parallel with the development of basic principles underlying the relationship between water and cereal grains, which has been described, is a complementary development of analytical methods for the determination of water. On the whole, it may be said that neither the importance nor the complexity of analytical procedures for the determination of water in cereals has been widely appreciated. The guiding principle has been to prefer the method that gives the highest moisture values, provided there are good grounds for belief that decomposition and loss of volatiles are negligible, or are no greater than the compensating error resulting from failure to remove all strongly adsorbed water. Simplicity and convenience of apparatus and technic, combined with rapidity, have also been factors in the choice of analytical methods.

In this section various aspects of the determination of moisture content will be considered. Sources of error that are common to most methods are discussed first. The individual methods are then discussed by classes—air-oven, vacuum-oven, distillation, chemical, and electrical methods. Recommended methods for cereals and cereal products and comparative data on the reproducibility and accuracy of the various methods are summarized in the final two subsections.

General Sources of Error

Because cereal grains are composed of kernels of appreciable size, and because these kernels possess a definite heterogeneity in chemical composition, the determination of moisture is subject to serious sampling errors. Most moisture methods for whole grain involve grinding the sample and

this creates an additional hazard, namely, loss or gain of moisture during grinding. These and other general sources of error merit brief discussion.

Sampling. When grain kernels of different moisture contents are mixed, moisture migrates readily from the wetter to the drier kernels. This tendency may create a false sense of security in sampling bulk grain for moisture determinations, for uniformity in final moisture contents of individual kernels is not attained. This point was demonstrated by Fisher and Jones (34) who mixed pairs of wheats of different moisture contents. Though equilibrium was achieved within a few days, the wetter wheat remained as much as 1.2% higher in moisture content, even in one experiment lasting 3½ years. A study of moisture contents of single kernels, undertaken by Oxley (62), adds further evidence of this phenomenon. Even in a sample of homogeneous origin that had been stored for several months the standard deviation of moisture contents of individual kernels was about ±0.2%. The standard deviation was about twice as great for samples recently dried or wetted. In mixed samples, such as a mill mix of English and Canadian wheats, standard deviations of over 1% were observed. In these samples, however, equilibrium had not yet been reached. This variability in the moisture contents of individual kernels emphasizes need for sound sampling procedures.

Two stages of sampling can normally be distinguished: first, sampling of the bulk lot; and second, laboratory subsampling. Though it is well known that wide differences in moisture content may occur in different parts of a bin or other bulk lot of grain, little attention appears to have been paid to the effects of bulk sampling errors on the total error of the moisture determination. Perhaps the principal difficulty is that adequate sampling is generally too expensive; custom appears to dictate sampling technics for bulk lots of cereal grains and their products, to which seller and buyer agree. If there is no bias in the bulk sampling, as seems probable, errors for individual lots cancel each other in the long run.

A second error is introduced when the bulk sample is resampled in the laboratory. This error is probably reduced by widespread use of Boerner and similar sampling devices. The common practice of taking one bulk sample, grinding a single subsample, and making duplicate determinations on the ground material, serves only to check laboratory errors. But even under the best conditions, an appreciable sampling error can be detected. For example, Cook, Hopkins, and Geddes (27) report a standard error of sampling of ±0.11% for replicate samples of wheat ground separately. It should be emphasized that an analytical result refers only to the sample tested, and that it is the sampling which relates the result to the bulk lot.

Preservation of Samples. A completely filled tin with triple-tight

pressed top, hammered down firmly, appears to be satisfactory for storing grain for moisture determinations. The small pliofilm sacks now available, which can be closed with a rubber band around the gathered neck, also merit investigation. But, no matter what type of container is used, the best advice is still to make the moisture determinations as soon as possible after the sample is taken.

Flour is more difficult to preserve than whole grain. The common practice of keeping flour for moisture determinations in a large ointment tin, sealed with adhesive or cellulose tape, appears unsatisfactory. The need for absolutely airtight containers was emphasized by Leatherock (47a) in 1922 after a survey of moisture determinations in 69 laboratories. Anderson (1), reporting for the National Check Sample Service of the American Association of Cereal Chemists in 1947, noted that the histogram for errors of the moisture determinations was not symmetrical; the bias toward low moisture was attributed to drying out of some samples during shipment to distant laboratories. Triple-tight pressed-top tins, instead of taped ointment tins, were suggested as a possible solution.

In cereal control laboratories the problem of preserving samples for moisture determinations is generally avoided by making the analysis promptly. Moreover, in a laboratory, samples can be conveniently stored in glass sealers or fruit jars and similar containers with rubber gaskets. Accordingly, the chief difficulty occurs when samples must be shipped from one point to another, e.g., for referee purposes; careful attention to airtight packing is then required.

Grinding. If material for moisture determination must be ground, this operation presents a considerable hazard; loss of moisture to the air or sometimes gain of moisture from the air may take place.

The two-stage drying method has been advocated to overcome this difficulty with grain of over 13% moisture (3, 27). A sample of 100 g. or more is first allowed to dry on a tray to equilibrium with the air; the moisture loss is obtained by weighing. A subsample is then ground for determination of the remaining moisture. Cook *et al.* (27) compared the two-stage and single-stage methods for Wiley and Hobart grinders, and for vacuum and air-oven (130°C.) methods. Their data (Table I) show that the two-stage method gave higher results: with wheat of about 11% moisture, the difference was about 0.2%; with wheat of about 19%, differences of up to 0.6% were found. The Wiley mill gave slightly higher results than the Hobart; it was concluded that the heating in the latter mill caused greater losses of moisture than the longer exposure in the Wiley mill. Results of a similar order are reported for grinding by Sair and Fetzer of the Corn Industries Research Foundation (72). Losses of moisture of 0.38% for corn of 13.7% moisture, and of 0.57% for corn

TABLE I

PERCENTAGE MOISTURE INDICATED BY VACUUM AND AIR OVENS USING DIFFERENT GRINDERS AND METHODS OF DRYING (27)

Sample No.	Vacuum Oven, 5½ hr.		Vacuum Oven, 16 hr.		130°C. Air Oven, 1 hr.	
	Wiley Mill	Hobart Grinder	Wiley Mill	Hobart Grinder	Wiley Mill	Hobart Grinder
Wheat ground directly (single-stage method)						
1	11.22	10.28	11.45	10.38	11.18ª	11.66
2	13.42	13.46	13.65	13.60	13.45	13.86
4	16.15	16.30ª	16.48	16.51ª	16.43	16.52
5	18.37	18.13	18.76	18.30	18.64	18.70
Wheat dried to equilibrium with atmosphere before grinding (two-stage method)						
1	11.40	11.56	11.88	11.68	11.70	11.86
2	13.64	13.69	14.02	13.96	13.76	13.96
4	16.48	16.16	16.77	16.31	16.72	16.46
5	19.02	18.68	19.42	18.72	19.19	18.90

ª Single determination only; duplicate lost.
All other figures are the averages of duplicate determinations.

of 17.6%, are cited as typical for grinding in a small Wiley mill.

The objection to the two-stage method is that it prolongs the determination. Cook *et al.* (27) report that 72 hours were required for samples to reach equilibrium on shallow trays ventilated with a fan. The Corn Research Foundation (76) suggests that 14 to 24 hours will suffice if drying is done in a warm, well-ventilated place. Precautions in the use of one-stage and two-stage methods have been consolidated in the Service and Regulatory Announcements No. 147 of the U.S.D.A. (89). For accurate work, the two-stage method appears essential. It should be used for calibrating all standard reference methods.

It seems probable that grinding of cereals introduces a biased error into most routine moisture results. This danger is increased when the moisture content is high and when large numbers of samples are ground consecutively in a burr mill which rapidly becomes hot. A convenient and efficient mill, which is essentially self-cleaning and water-cooled, could be used to advantage in most cereal laboratories. In the meantime, the Wiley mill, which is slow, and cumbersome to clean between samples, appears to be preferred for accurate moisture determinations.

Weighing of Dried Material. Finely ground grain, flour, and other cereal products pick up moisture rapidly when completely dry. Precautions that must be taken to prevent postdrying errors include: use of moisture dishes with tight covers; prompt closing of dishes when oven is opened; rapid transfer of dishes from oven to desiccator; and rapid weighing. Needless to say, dishes must be cool before they are weighed,

or convection currents in the balance case will introduce a weighing error.

The analyst should also be familiar with the limitations of the common desiccator and desiccants. King (46) showed, for example, that as much as 7.5 mg. may be gained in an hour by a 5-g. sample of oven-dried flour allowed to remain in presence of calcium chloride in a conventional desiccator. Basic references on this subject are listed in King's paper.

Moisture dishes do not last indefinitely. Dented tins with badly fitting covers should be promptly discarded. A set of metal dishes of uniform tare weight, adjusted by filing, speeds weighing and represents a sound investment of time.

Air-Oven Methods

Because of their convenience, air-oven methods of various types are widely used in control laboratories for determination of moisture in grain. All these methods are highly empirical. The loss of weight, reported as moisture, is a function of the temperature and time of drying; increasing either causes an increased loss of weight. Moreover, increasing the temperature causes an increased loss of weight that cannot be obtained at a lower temperature, no matter how long the sample is heated. It has been shown, by measurement of evolved carbon dioxide, that with temperatures over about 80°C. part of the loss of weight results from decomposition of the product. Accordingly the use of high temperatures to obtain more rapid procedures can be justified only on pragmatic grounds.

Ovens ranging from simple water-jacketed types to elaborate equipment with forced air circulation and built-in balances are in wide use. Temperatures range from about 98°C. for water ovens to about 155°C. for the most rapid methods. A number of typical methods are discussed in the following subsections.

Water-Jacketed Ovens. Double-walled ovens permitting a water jacket on three sides, top, and bottom, but not for the door, are still widely used in places where electricity is not available and gas must be used for heating the oven. The temperature of the boiling water and hence of the oven varies with atmospheric pressure and with altitude. When the boiling temperature is 100°C. the temperature of the center of the oven is about 98.5°C.; a cooler area exists near the door. The boiling point tends to rise with any increase in the concentration of salts, so that it is best to use distilled water. Steam-jacketed ovens are also used for moisture determinations in some laboratories.

With ground cereals and flour, drying to essentially constant weight in a water oven requires about 5 hours. Consistent results can be obtained in one laboratory, but the interlaboratory variation is probably

no less than for other methods. Water ovens give results that average about 1.9% less than the vacuum oven. Since the latter method (see below) is now widely adopted as a reference standard, at least on the North American continent, the water oven is considered to give erroneous results. In addition the method is too slow for many purposes.

Electric Convection Ovens. A wide variety of electrically heated ovens is on the market in various countries. Not all of these are equally well suited for moisture determinations; pertinent points of construction thus merit discussion.

In general, precision of control and uniformity of temperature at different positions in the oven are the principal criteria of suitability. Precision of control when the oven is closed requires a suitable thermoregulator with a sensitivity of ±0.5°C., or less, that will maintain its setting without requiring constant adjustment. In addition, the heating units should be adjusted to give a reasonably rapid on-and-off cycle (say, 15 minutes or less) for an oven with a normal load of samples.

Control of temperature variations at different positions within the oven is difficult to achieve. In the best ovens pains are taken to distribute the heating units and to provide internal air ducts to control convection currents so as to minimize temperature variation with position. Adequate insulation and a double door are also required. The best air oven known to the authors shows space variations of ±3.0°C. Many ovens have space variations that are two or three times greater. The basic difficulty lies in the fact that air is a poor conductor of heat.

As a result of these temperature variations with position, sound practice requires that samples be placed only on one shelf of the oven, and that they be kept away from the door and walls. The bulb of the thermometer should be level with the samples; moreover, the fewer the samples and the more closely these surround the thermometer bulb, the greater the uniformity of the results. Increasing the number of samples not only keeps some further from the center of the oven, but also increases the time that the oven remains open during loading and unloading. Drying periods are measured from the time the oven attains the specified temperature; but the final moisture is a function of the total heating period. Accordingly, if the oven cools excessively during loading, the samples will actually be exposed to a longer heating period.

Variations of temperature with position in the oven and some of the effects of opening the oven door may be overcome by using a 0.5-in. sheet of aluminum as a shelf. This procedure was introduced by Sandstedt (78). The high heat conduction of the aluminum brings the samples rapidly to oven temperature and also reduces temperature variation with position. Other conditions being unchanged, introduction of an alumi-

num shelf gives slightly higher moisture results.

A fair number of time-temperature procedures are used with ordinary convection ovens. For flour, drying at 130°C. for 1 hour is probably the most widely used method in North America. Ground cereals are frequently dried under the same conditions. Additional information on other products and comparisons of results of different procedures are discussed in later subsections.

Forced-Draft Ovens. Though variations of temperature with position can be minimized by circulating the air in the oven with a fan, and though a number of ovens of this type are available, the procedure appears to be little used in determining the moisture contents of cereals and cereal products. The Brabender semi-automatic moisture tester is an exception to this generalization. A small fan is used to circulate air in this oven, but its distinguishing feature is a built-in automatic scale. A photograph of the Brabender oven is shown in Figure 2. The oven holds ten 10-g. samples in flat tared dishes, held equidistant from the center of the oven on a shelf that can be rotated by an external knob. After the specified drying period, usually 1 hour at 130°C., each dish can be brought into position at the front of the oven, and engaged with the balance mechanism by means of a lever. The moisture content is indicated directly on an illuminated scale. Eva, Milton, and Geddes (31) found that this procedure gave the same results for flour as are obtained with the DeKhotinsky air oven by drying for 1 hour at 130°C. Since the samples are not removed and cooled for weighing, there is an appreciable saving of time. This, together with all-round convenience and the reduced sampling error given by a large sample, makes the equipment attractive. It is widely used in cereal laboratories for ground grain, flour, and other cereal products.

Rapid Air-Oven Methods. The Sandstedt aluminum plate method has already been mentioned. For this procedure the temperature is raised to 140°C., measured by immersing the thermometer bulb in a tin of sand resting on the plate. A 2-g. sample of flour is dried in 15 minutes. A 0.5-in. aluminum plate is also used for cooling the samples, which requires 2.5 minutes, or slightly more. No desiccator is used provided conditions are such as to cool the samples in less than 5 minutes. The method can be used for ground cereals, but this is not generally recommended; the drying time must be increased to 20 minutes or more. Stein (87) modified the method for ground malt by adopting a temperature of 125°C. and a 15-minute drying period.

A second rapid method, requiring a special Carter-Simon oven (Fig. 2), is in wide use in Great Britain and Europe. The oven is operated at 155°C. and is designed to take three moisture dishes held in a channel

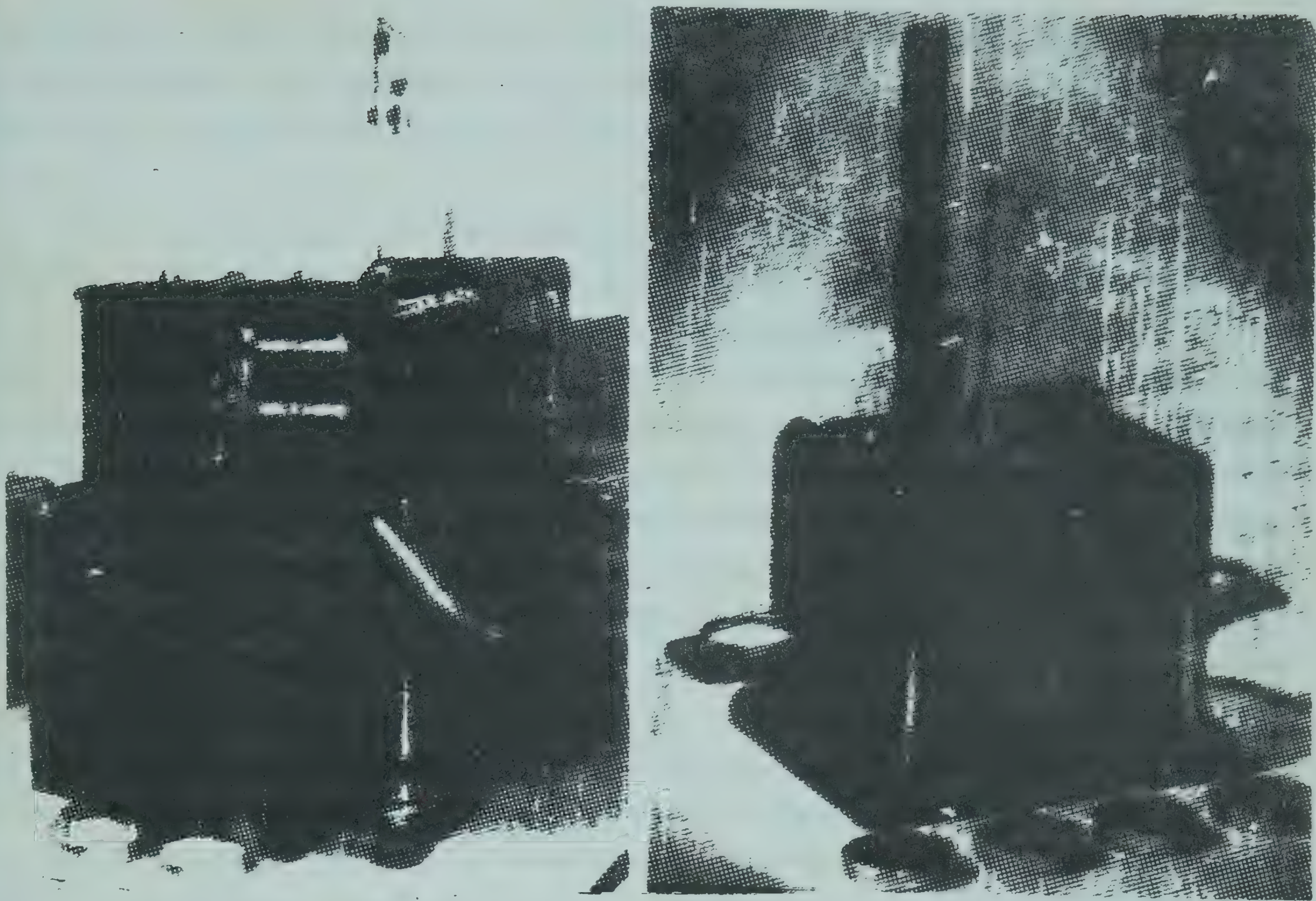


Fig. 2. Left, Brabender semi-automatic moisture tester; right, Carter-Simon rapid moisture tester.

passing through the oven. Small flap doors are provided at either end. One dish is inserted at one end of the channel each 5 minutes, and one is pushed out and removed at the same time at the other end of the channel. Each dish is thus moved to a new position at 5-minute intervals and occupies three different positions for 5 minutes each during the 15-minute heating period. One disadvantage of the method is that it requires constant attention. This oven is described in more detail by Coleman and Dixon (24) and Kent-Jones and Amos (45). Putnam (68) found that Carter-Simon results for flour agreed closely with those obtained with the 130°C. air-oven method.

The Meihuizen procedure has a still shorter heating time. The flour sample is heated in a jacketed bath of boiling *o*-dichlorobenzene (b.p. 179°C.) for 12 minutes. Since the apparatus is more cumbersome than an electric oven, it has not achieved much popularity.

The Chopin *Etuve Rapide* (21) has a novel feature. The sample is heated in a small oven in a limited amount of air at 200°C. and the vaporized water is brought into contact with calcium carbide. The acetylene which is generated issues as a jet on the top of the oven. The gas is lighted, and the end of the drying is indicated when gas evolution ceases; the actual end point is taken as the time when the flame has passed its maximum and dies down to a specified size. The sample is

then removed, cooled, and weighed. For flour, about 4 to 5 minutes are required for the actual drying, and 6 to 7 minutes for ground grain. It is claimed that the results check well with those obtained by other methods.

Vacuum-Oven Method

The usual vacuum-oven method involves drying to constant weight at 98° to 100°C. at a pressure of 25 mm. of mercury or less. This method is "official" for ground cereals, flour, and most other cereal products, according to the Association of Official Agricultural Chemists. It is listed in *Cereal Laboratory Methods,* and is widely recognized as a standard reference method. Aside from its status as an "accurate" method (see final section), the vacuum-oven procedure is highly reproducible, at least for a single oven. Accordingly, it serves admirably for checking sampling errors and as a reference method for calibrating other less reproducible procedures.

Because of its reputation, the vacuum-oven method merits more critical discussion than would be appropriate for most other methods. While drying to constant weight is advocated, precise work (9, 27) suggests that this requires much longer than the 5 hours usually suggested or the overnight drying often used. However, constancy within less than 0.1% moisture is usually obtained within 16 hours (27).

The reproducibility of the method in different ovens, whether in the same or different laboratories, does not appear to have been established with certainty. Cook *et al.* (27), working in the Grain Research Laboratory, Winnipeg, with two DeKhotinsky ovens with oil-jacketed vacuum chambers, reported an average difference of 0.07% moisture between results obtained in the two ovens. In the same laboratory, differences of 0.1% for two similar oil-bath ovens, and of 0.2% between an oil-jacketed vacuum oven and an air-jacketed vacuum oven, have since been observed.

In recent work at the Grain Research Laboratory, Winnipeg, these differences between ovens have been traced, by use of thermocouples, largely to *shelf* temperatures. A thermometer, with its tip at the level of the top of moisture dishes resting on the shelf, is heated mainly by radiation; whereas the shelf itself—and presumably the samples—is heated by both radiation and by conduction of heat from the oven walls. The shelf is normally about 1°C. hotter than the thermometer bulb, and this difference is increased if the shelf fits tightly against the walls so that conduction is facilitated. Moreover, with a wire or lattice metal shelf of the type usually supplied, a difference of 3°C. in shelf temperature may occur from back to front of the oven. This difference can be reduced by lining the inside of the inner glass door with aluminum foil to reduce loss of radiated heat from the front of the oven through the glass. Greater

uniformity of shelf temperature (within ±0.1°C.) can be obtained by using a 0.5-in. aluminum shelf that makes good contact with the walls. In this case, however, the temperature at which the oven is set should be that of the shelf.

The temperature of 98°–100°C. specified for the vacuum-oven method suggests than an accuracy of ±1.0°C. is good enough. While this is probably adequate for most routine work, precise studies demand closer specification of temperature. Mercury-in-glass thermoregulators that can be set to a very close tolerance and that will maintain the shelf temperature well within ±0.1°C. can certainly be obtained, and can be installed readily in most vacuum ovens. Provided with suitable relays, these thermoregulators maintain their setting almost indefinitely and give trouble-free operation. Accordingly, the installation appears worth while even for routine work.

A closer specification for pressure would also be advantageous. For some products, such as vegetables and cheese, an air bleed-in is required. Specifications for vacuum drying of cereals do not state whether the required vacuum (25 mm. of mercury or less) is to be maintained with or without the bleed-in. Possibly it is assumed that most vacuum ovens are not completely vacuum-tight, and that a bleed-in occurs whether specified or not. If this is so, a controlled bleed-in might well be stipulated.

Under existing specifications the vacuum oven gives more reproducible results within one oven than any other method. Moreover it seems relatively certain that the vacuum-oven method gives the most reproducible results between different ovens and between different laboratories. However, for use as a reference method in calibrating other procedures and most certainly as a research tool, vacuum ovens should be more closely standardized in construction (particularly with reference to shelf, door, and thermoregulator) and should be operated with a more precisely specified technic.

Distillation Methods

Two distillation procedures that are classed as standard methods warrant discussion. The first of these is the Brown-Duvel method. For many years this was the standard moisture method for grain inspection in the United States (23), and it is still the standard method in Canada (41); it is also listed as a method for cereals by the American Association of Cereal Chemists. The second standard distillation method is the toluene or benzene distillation. It is an official method of the Association of Official Agricultural Chemists for grain and stock feed, and is recommended by the Corn Industries Research Foundation as the official reference method for corn and certain corn products.

Brown-Duvel Method. This method was developed in 1907 (17) and

has found wide application for testing cereals on the North American continent. A drawing of the apparatus is shown in Figure 3. The equipment generally makes provision for heating six flasks simultaneously; four-, two-, and single-unit equipment is also available. A 100-g. sample of whole grain is heated in the flask with 150 ml. of nonvolatile oil to a specified cutoff temperature (180°C. for wheat). The hinged heating unit is then lowered to a predetermined position so that the oil-grain mixture cools to 160°C. The amount of water that is distilled into the graduated cylinder is read in milliliters and reported as percent moisture. Different cutoff temperatures are specified for different grains. The determination takes about an hour and, with a suitable bank of equipment, one man can make about 12 to 18 determinations per hour.

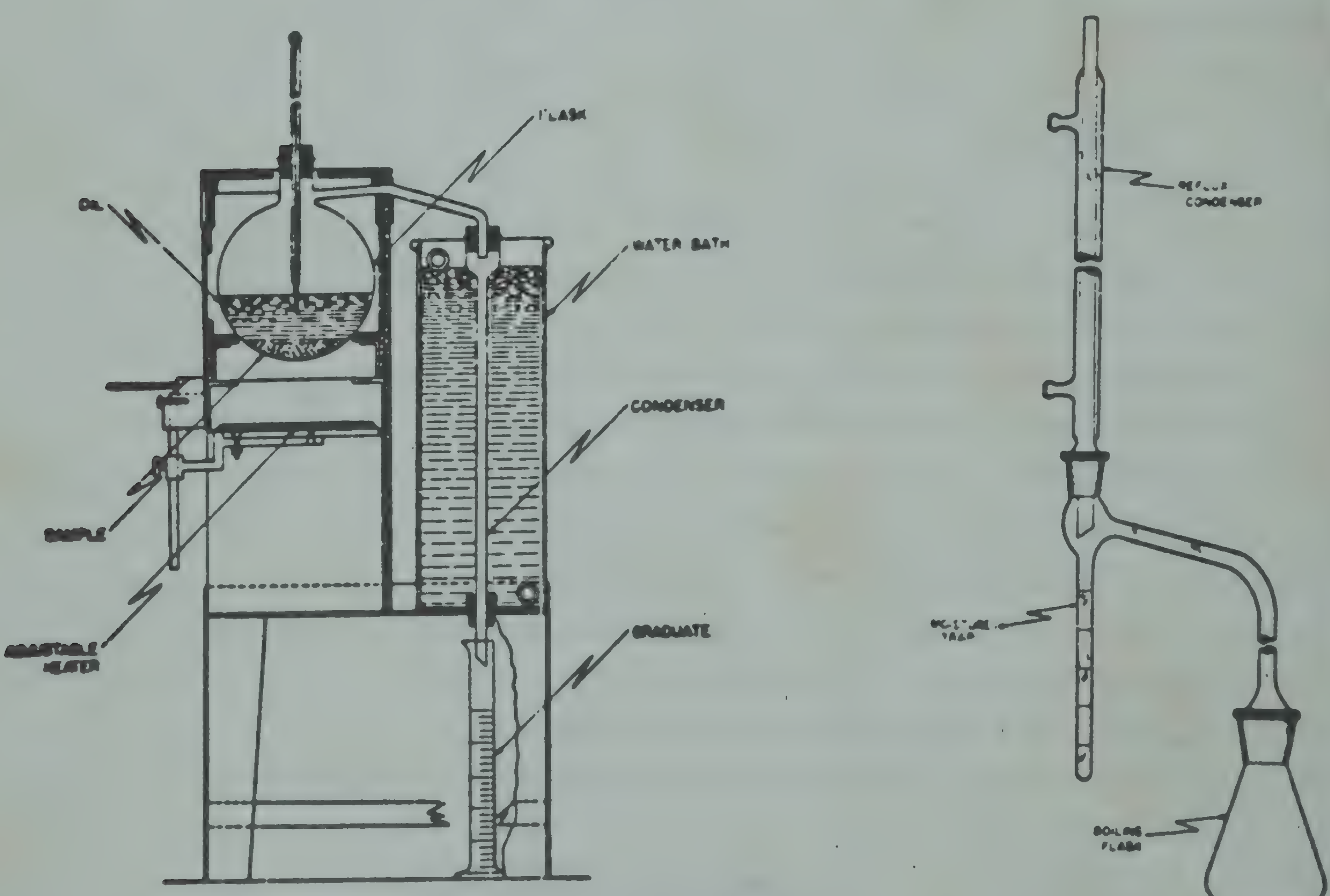


Fig. 3. Left, diagram of Brown-Duvel apparatus; right, diagram of Bidwell-Sterling apparatus.

The rate of heating is established and checked periodically by an "oil test" made with 450 ml. of oil in place of the oil-grain mixture. The heating time is adjusted by raising or lowering the heating unit so that the temperature reaches 153°C. above the initial temperature of the oil within 20±0.5 minutes (Canadian specification: 25±0.5 minutes).

The method has certain advantages. It can be readily taught to inexperienced persons. Only a relatively crude torsion balance is required to weigh 100±0.1 g. The remainder of the equipment is reasonably

rugged or easily replaced. Standardization of the equipment requires no accessories. The Brown-Duvel method can thus be used in elevators where other methods, involving weighing of small samples on fine balances, would not be feasible.

On the other hand, the method is highly empirical. Precise results can only be obtained with standard equipment and by following detailed specifications covering procedure. Because a relatively high temperature is used for the distillation, some of the water measured results from decomposition of organic matter. Where gas burners or alcohol lamps are used in place of electric heaters, accurate and reproducible results are much more difficult to obtain. The criticism that the Brown-Duvel method underestimates moisture content can be overemphasized. The method was originally standardized against the water oven, a procedure which is still used for corn although for other grains it is standardized against a 130°C. 1-hour air oven. The method can be restandardized against the vacuum oven or other method, or its results can be corrected to vacuum-oven basis by means of a regression equation (27, 40). Such an equation takes account of the increase in underestimation with increasing moisture content, which is a characteristic of the Brown-Duvel method.

Toluene and Benzene Distillation Method. The reference method recommended for corn and certain corn products, which is also suitable for other cereals and cereal products, is essentially that described in 1925 by Bidwell and Sterling (11). Detailed specifications have been drawn up by the Corn Industries Research Foundation (76).

A drawing of the apparatus is shown in Figure 3. A sample of 20-30 g. of corn, ground in a small Wiley mill with 20-mesh sieve, is introduced into the flask with 75 ml. of toluene. Distillation is started slowly (1–2 drops per second), but is speeded up (2–4 drops) after the first half-hour, and is continued for 48 hours. Moisture collects in the graduated trap from which the excess toluene flows back into the flask. Careful attention to specified details of technic and standard apparatus are required for accurate results.

Toluene distillations are used for corn, corn gluten meal, and corn oil meal; and benzene distillations for corn gluten feed and sweetened feed. Though the method is comparatively slow, it should have wide application for other cereals and cereal products, and has much to recommend it as a basic reference procedure.

Chemical Methods

Two chemical methods have been used for rapid determination of the moisture content of flour, namely, Karl Fischer titration, and production of acetylene by mixing flour with calcium carbide. Both methods are

influenced by the fineness of the material and are therefore unsatisfactory for ground grain. Neither has yet gained wide popularity, even for flour.

The Karl Fischer titration depends upon a stoichiometric reaction of the Karl Fischer reagent with water. The reagent is composed of iodine, sulfur dioxide, pyridine, and methanol. The reaction takes place in two steps:

$$\begin{aligned} &C_5H_5N \cdot I_2 + C_5H_5N \cdot SO_2 + C_5H_5N + H_2O \\ &\quad \rightarrow 2\ C_5H_5N \cdot HI + C_5H_5N \cdot SO_3 \end{aligned} \qquad (1)$$

$$C_5H_5N \cdot SO_3 + CH_3OH \rightarrow C_5H_5N(H)SO_4CH_3 \qquad (2)$$

These equations show that each mole of water requires one mole of iodine, one of sulfur dioxide, three of pyridine, and one of methanol. In practice, however, an excess of sulfur dioxide, pyridine, and methanol is used and the strength of the reagent thus depends upon the concentration of iodine.

The sample in which water is to be determined is dispersed in dry methanol and is titrated with the reagent. The end-point change is from chromate yellow to the red-brown of iodine. Reagents, titrating flask, and burettes must be protected from atmospheric moisture. Both the Karl Fischer reagent and various forms of titrating apparatus are available commercially.

Where it can be demonstrated that there are no interfering side reactions, the Karl Fischer method may be considered as a primary standard method for the determination of water. In presence of biological material, however, it must be standardized in terms of another reference method.

Fosnot and Haman (35) studied the application of Karl Fischer reagent to the determination of moisture in a variety of cereals and cereal products. They found that for each kind of material tested the fineness of grind and contact time with the Fischer reagent must be determined accurately. As might be expected, these factors affect the completeness of the reaction between water in the sample and the reagent. If due care is taken the method is quite satisfactory. Results as reported by Fosnot and Haman agreed well with those obtained by oven methods.

The reaction between calcium carbide and the water of a sample, resulting in the production of acetylene, has been used to estimate moisture in many materials. The measurement is made in either of two ways: by allowing the acetylene to escape from the system and noting the loss of weight: or by keeping the system closed and measuring either the volume or the pressure of the gas produced. Blish and Hites (13) have devised a simple apparatus for flour, based on the measurement of

pressure, which yields good results in approximately 5 minutes. Similar equipment is now on the market. The equipment is calibrated with pure water so that when the pressure is read the amount of water in the sample is determined by direct reference to a graph. Actually, not all of the water in the flour reacts with calcium carbide. But the amount not reacting is a constant, 0.0455 g. per g. of flour, and this figure is added to the result. Results for flour check well with those for the 130°C. air oven, the greatest difference observed being 0.32%. Since results are recorded as pressure, the method can presumably be calibrated in terms of the vacuum oven or other standard method. Objections to the use of the carbide method are the odor of the acetylene, its inflammability, and the disposal of carbide residues. So far as the authors are aware, little use is being made of this type of equipment.

Electrical Methods

During the past 20 years or so, a considerable number of electrical instruments have been designed for estimating the moisture content of various materials, including cereal grains and their products. Some have been unsatisfactory; they have languished on the market for a year or two and then disappeared. One, the Tag-Heppenstall meter, has stood the test of 20 years in wide use and still maintains its popularity. During the past few years, three or four promising new meters have become available, but more experience is required to determine whether any of these will find a permanent place in grain-handling and cereal-processing industries.

All meters introduce grain into an electrical circuit and measure the resistance and/or dielectric constant of the grain. With one exception, meters that depend primarily on measuring the electrical resistance of the grain have given results most closely correlated with moisture content. Three resistance-type meters and two dielectric types, which appear most satisfactory for estimating moisture content of grain or flour, are briefly described in the next two subsections. The limitations of electric meters in general are then discussed.

Resistance-Type Meters. The three resistance meters that appear most suited for grain are the Tag-Heppenstall, Universal, and the Marconi (type TF 933). The Marconi meter is also suitable for estimating moisture content of flour.

In the Tag-Heppenstall meter (Fig. 4), the electrical resistance of the grain is measured as it passes between two corrugated steel rolls that serve as electrodes. One is motor-driven (or hand-driven) and the other idles. Grain is poured into the hopper and is partially crushed to provide good electrical contacts as it passes between the rolls. A selector switch on the separate instrument box is turned to one of eight positions that

control the range of values indicated by a galvanometer, and the position of the galvanometer needle is read. The temperature of the grain must

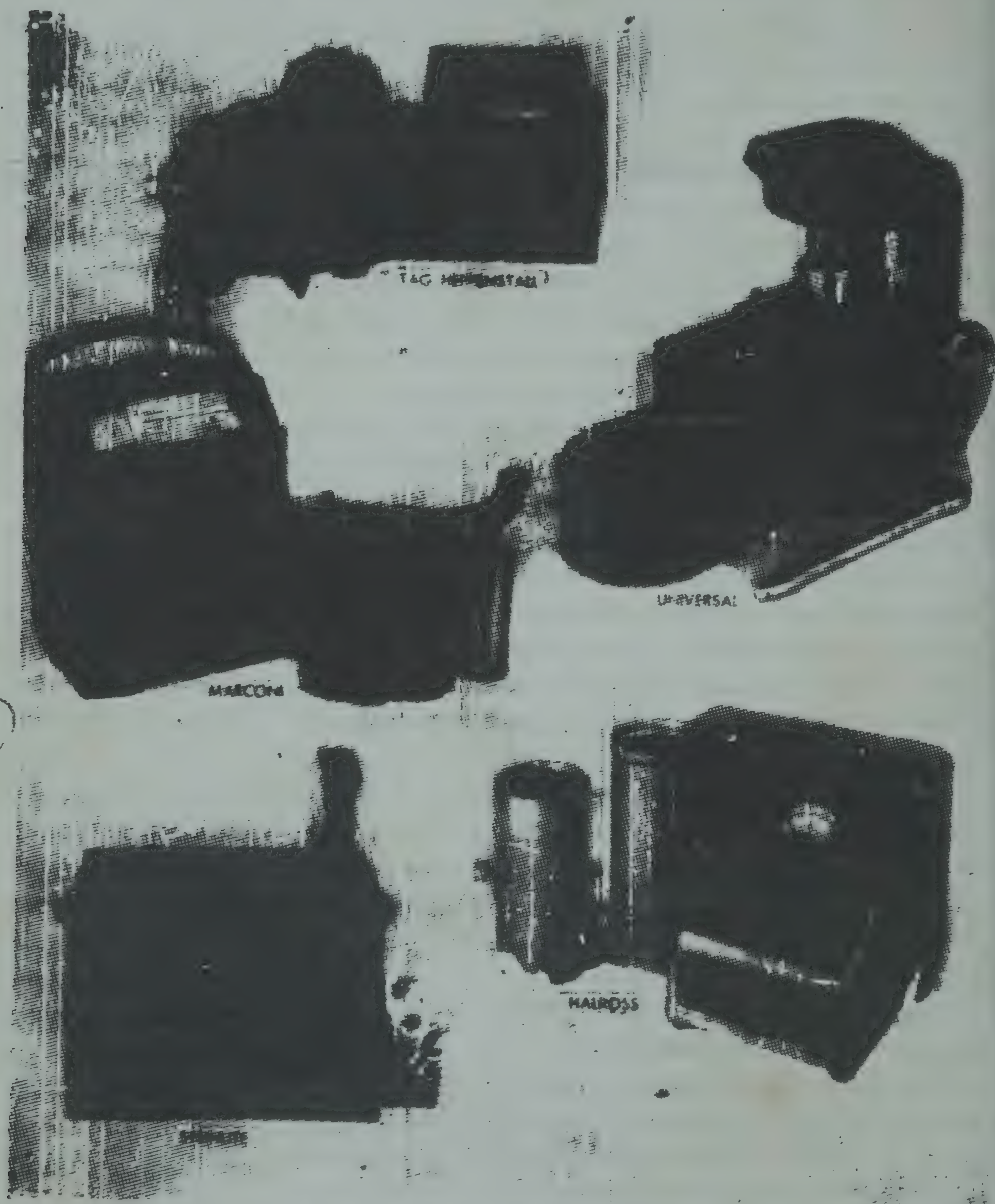


Fig. 4. Electrical moisture meters.

be known, and charts are provided to convert temperature and galvanometer readings to moisture content.

The instrument measures the average resistance or conductance of the kernels passing between the rolls at any instant. The galvanometer

needle tends to flicker, particularly with mixtures of kernels with different moisture contents, but its mean position can be readily and accurately estimated. The spacing between the rolls is critical. Identical roll spacing is used for wheat, barley, and oats. But the space must be narrowed for flaxseed by introducing different shims. A different set of rolls, with larger corrugations and wider spacing, is used for corn and soybeans.

The Tag-Heppenstall meter appears to be one of the most accurate instruments now available for testing grain; the standard error of estimation in testing hard spring wheat is about $\pm 0.23\%$ (28, 29, 40). It is certainly the most rapid; tests can be made in 10-20 seconds. When it is necessary to know only whether the moisture content is over or under a specified value, tests can be made at a rate of 8 to 10 a minute. The meter has the further advantage that calibration charts are available for various types of wheat and for almost all other grains (25a). The meter cannot be used for flour and other cereal products.

One objection to the Tag-Heppenstall meter is the difficulty of maintaining the calibration. As the rolls and bearings wear, the spacing between the rolls increases and lower results are obtained. An increase of 1/1000 in. causes a decrease of about 0.03% in the moisture reading. Moreover, calibration cannot be reestablished by adjusting the space with feelers to a specified value; for the reading is affected not only by the distance between rolls, but also by the sharpness of the corrugations. Badly worn rolls must eventually be replaced; but in the interim, periodic recalibration must be undertaken by an empirical process. A series of about 20 samples of known moisture content are tested; if the results are low the space between the rolls is reduced by inserting shims behind the idling roll, and the samples are retested. This process is repeated until a correct result is obtained. An estimate of the shim thickness required can be made by allowing 1/1000 in. in roll spacing for 0.03% in moisture content.

In the Universal meter (Fig. 4), a hand-driven megger establishes a voltage across a sample of pressed grain and electrical resistance is indicated on an ohmmeter of the dynamometer type. The instrument thus requires neither batteries nor power supply. A test is made on a 20-g. sample weighed to the nearest kernel. This is transferred to a steel cup with cylindrical plastic lining and an internal diameter of 1⅝ in. The cup is placed under the ram of a screw press operated with a ratchet lever, and the grain is pressed to specified thickness, 0.40 in. for wheat, which is indicated by a micrometer device on the instrument. The megger is then cranked rapidly and the meter is read. An armored thermometer is provided for reading the temperature of the grain. The test requires about 1.5 minutes, which is also about the time required for tests on

most electrical meters other than the Tag-Heppenstall. A circular sliding scale for converting temperature and meter reading to moisture content is provided on the front of the instrument. By adjusting the weight of the sample and the thickness to which it is pressed, the same conversion scale is said to be accurate for all grains.

Investigation (40) of a prototype of the Universal meter showed that it was almost as accurate as the Tag-Heppenstall meter. The standard error of estimate was $\pm 0.28\%$. It was noted, however, that the meter was not correctly calibrated for wheat. Provided that the present model is accurately calibrated for each cereal and for temperature, it has several advantages. The meter should maintain its calibration, and is rugged enough to require little upkeep under normal conditions. Moreover the meter can be used for a wide variety of seeds, including flax and mustard, without modification. The authors have not found it possible to use the Universal meter conveniently for testing flour, which cannot be readily compressed in the cell.

The Marconi (model TF 933) is a battery-operated instrument of the resistance type. It has been described in detail by Brockelsby (15). The test cell, shown on the right in Figure 4, is based on a C-clamp holding a small cell (1 in., internal diameter) in which the sample is pressed at 1,000 lb. per sq. in. The pressure is applied by a hand-operated screw, supplied with a calibrated spring prestressed so that the required stress is applied with a half turn of the screw. Electrodes consist of two circular rings inset into the bottom of the cell. The ground grain or flour is compressed against these coplanar electrodes, and as the current penetrates the sample only to a depth of the order of the electrode separation (0.04 in.), the quantity of sample in the cell is unimportant above a certain minimum. This dispenses with the need for weighing.

Provision is made for standardizing the circuit, and the meter reading is conveniently taken through a window in the instrument case. The scale visible at the top of the photograph is a slide rule for converting instrument readings to moisture content, with correction for temperature. A sliding scale is clipped to the instrument above the permanent scale to complete this assembly, and different scales are provided for different materials.

The instrument appears to be well adapted for testing the moisture content of flour. With grain, the sample must first be ground. Brockelsby claims that the loss of moisture is negligible during grinding in the small enclosed hand-driven mill provided with the instrument. Rough tests can be made on whole wheat when this is too wet to grind, say, over 22%.

Recent investigations made in the Grain Research Laboratory, Winni-

peg, have established the standard error of estimate for wheat at about ±0.23%.

Dielectric-Type Meters. The two dielectric-type meters that appear most useful for testing cereals and their products are the Steinlite and Halross.

A photograph of the current model of the Steinlite meter is shown in Figure 4. To operate, power is turned on and the circuit is balanced by setting the dial selector to a red button and turning a knob until the galvanometer reads 45 on the scale. A weighed sample (150 g. of wheat) is put into a drop-bottom loading funnel. By tripping a release trigger the grain is introduced into a narrow cell of the meter, the long walls of which are plates of a parallel plate condenser. To obtain the meter reading on the sample, the dial selector is rotated counter-clockwise to select the correct radio frequency range, and both the galvanometer reading and the button designation are recorded. Percent moisture is obtained from the instrument reading with the aid of appropriate tables. In a recent survey (40), comparison of an earlier model of the Steinlite meter with the vacuum oven gave an error of estimate of about ±0.4% moisture on hard red spring wheat.

Of the dielectric-type meters available for testing grain, the Halross instrument is of special interest. A photograph is shown in Figure 4. A filling tube, with a simple dumping device, is provided for uniform loading of the circular cell which is readily detached for emptying. The central column of the cell is tapered to provide automatic correction of errors introduced by differences in the bushel weights of samples. Simple means are provided for checking the standardization of the circuit. Readings are made by turning a knob until a meter needle reads at a minimum; a scale on the instrument is then read and converted to moisture content with a calibration chart. As usual, the temperature of the grain must be known. Unpublished results obtained in the Grain Research Laboratory indicate an error of estimate of the order ±0.22%. Preliminary calibrations have been made for various grains and for temperature correction.

Information has been published on other electrical moisture meters within recent years (40, 70), but none of these appears to be as accurate at their present stage of development as the meters described above.

Other Types of Electrical Meters. Recent development of electrical sensing elements which can measure relative humidity accurately has made possible a novel approach to the measurement of water in cereal grains. It is claimed that the humidity of intergranular air rather than the absolute amount of water of grain is of primary importance. Accordingly, a method which measures the humidity of intergrain air pockets

has been proposed. Brockington, Dorin, and Howerton (16) present comparative data on corn by the new method and by the Brown-Duvel and vacuum-oven methods. At this time, however, it is premature to assess the significance of this development.

Various devices for the determination of moisture in grain and similar products are continually being developed. The following is the active list, at the time of writing, of the Grain Branch, Production and Marketing Service, U.S.D.A.

List of Rapid Moisture-Testing Devices for Grain and Related Products

Name of Device	Principle of Operation	Manufacturer or Distributor
All-Crop Moisture Tester	Direct heating (infrared)	American Crop Drying Equipment Company Crystal Lake, Illinois
"Aqua-Part"	Conductance	Otto Kuhne OHG. Apparate – u. Geratebau Frankfurt/Main—Niederrad. – Werk Kl. Krotzenburg, Kr. Offenbach/Main, Germany
Brabender Moisture Tester	Direct heating	Brabender Corporation Rochelle Park, New Jersey
Brown-Duvel Moisture Tester	Distillation	Seedburo Equipment Company 618 West Jackson Boulevard Chicago 6, Illinois
Carter-Simon Moisture Tester	Direct heating	Seedburo Equipment Company 618 West Jackson Boulevard Chicago 6, Illinois
Cenco Moisture Balance	Direct heating (infrared)	Central Scientific Co. 1700 Irving Park Road Chicago 13, Illinois
Chopin Rapid Moisture Tester	Direct heating plus chemical reaction	Thomas Robinson & Son, Ltd. Rochdale, England
Christie High Frequency Desiccator	High frequency dielectric heating	Phipps & Bird, Inc. 303 South Sixth Street Richmond, Virginia
Delmhorst Moisture Detector	Conductance	Delmhorst Instrument Company Boonton, New Jersey
Halross Moisture Meter	Capacitance	Canadian Aviation Electronics, Western Division, 387 Sutherland Avenue Winnipeg, Canada
Hart-Moisture-Meter	Conductance	Hart-Moisture-Meters Grand Central Terminal New York 17, New York
Hygrotester	Capacitance	Paul Lippke Mess—und Regel-Gerate (22b) Neuwied am Rhein, Germany
Kappa Moisture Meter	Capacitance	Toplis, Simpson & Co., Ltd. Sunleigh Works Sunleigh Road Wembley, Middlesex, England
Marconi Moisture Meter, type TF 933	Conductance	Canadian Marconi Company Marconi Building 2442 Trenton Avenue Montreal 16, Canada

LIST OF RAPID MOISTURE-TESTING DEVICES FOR GRAIN AND RELATED PRODUCTS

Name of Device	Principle of Operation	Manufacturer or Distributor
Marvel Moisture Tester	Direct heating (infrared)	R. W. Selman and Associates 1517 Walnut Street Kansas City 8, Missouri
National "15 Minute" Moisture Oven	Direct heating	National Manufacturing Co. Lincoln, Nebraska
N.P.L. Moisture Meter	Capacitance	Baldwin Instrument Co., Ltd. Dartford, Kent, England
Speedy Moisture Tester	Chemical reaction	Thos. Ashworth & Co., Ltd. Vulcan Works, Burnley, England
Steinlite Moisture Tester	Impedance	Fred Stein Laboratories 121 North Fourth Street Atchison, Kansas
Tag-Heppenstall Moisture Meter	Conductance	Weston Electrical Instruments Corporation Tagliabue Instruments Division 614 Frelinghuysen Avenue Newark 5, New Jersey
Tag-Dielectric Moisture Meter	Capacitance	Weston Electrical Instruments Corporation Tagliabue Instruments Division 614 Frelinghuysen Avenue Newark 5, New Jersey
Thwing-Albert Electronic Moisture Meter	Conductance	Thwing-Albert Instrument Co. Penn Street and Pulaski Avenue Philadelphia 44, Pennsylvania
Universal Moisture Tester	Conductance	Sheldrick Manufacturing Co. Upper Sandusky, Ohio

General Limitations. The electrical properties of grain do not appear to depend solely upon moisture content. It may be surmised that electrical properties are affected by the amount of salts in solution in the water in the grain. However, Paull and Martens (66) were unable to demonstrate any improvement in the correlation between meter readings and moisture content by taking ash into account as a possible means of estimating salt concentration. But they did show that, with meters in which the grain is not crushed, part of the error in estimating moisture is attributed to differences between samples in average kernel size and shape.

Whatever the causes may be, even the best meter may over- or underestimate moisture content by as much as 1% moisture on certain samples. This point is illustrated by the scatter diagram for the Tag-Heppenstall meter and the vacuum-oven method shown in Figure 5. The moisture value for the sample represented by point A is overestimated by more than 0.5%; whereas B is underestimated by almost 1.0%.

In spite of these occasional large errors, the electric meters appear to have a place in testing for moisture content. They possess the very important advantage of speed and make possible moisture testing where it was out of the question by the slower methods. If properly calibrated

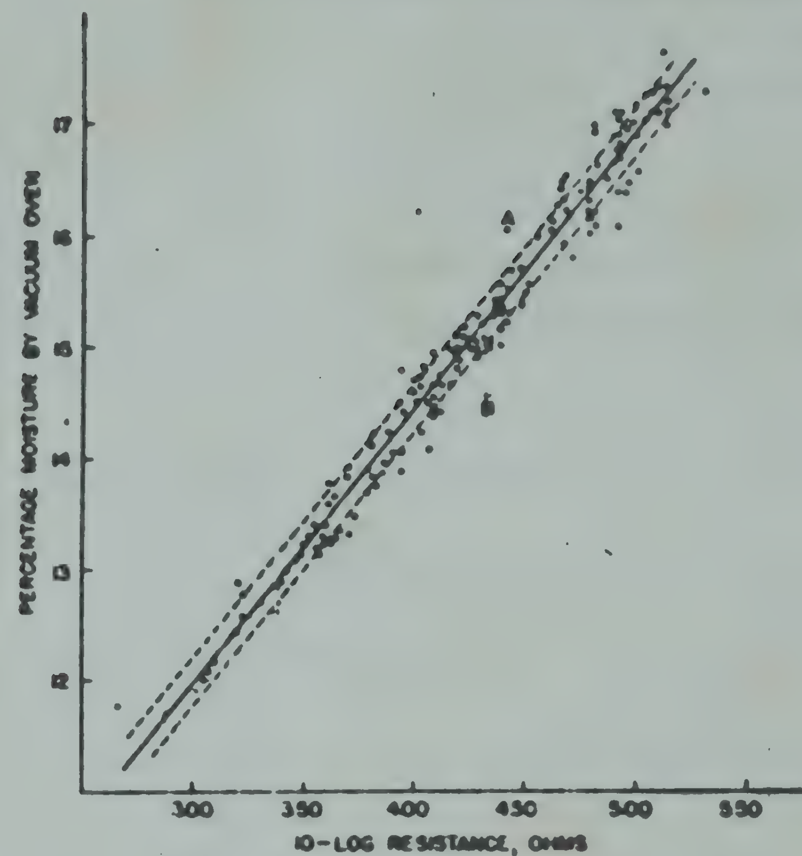


Fig. 5. Scatter diagram of Tag-Heppenstall meter against vacuum oven results illustrating over- and underestimation of moisture.

they will give accurate results, on the average, over any considerable number of samples. Thus the mill buying grain consistently on the results of electrical tests for moisture content should neither gain nor lose in the long run. The same may be said for the farmer who is prepared to sell grain on the basis of electrical moisture tests; what may be lost on certain individual lots should be gained on other lots. Moreover, when a number of carlots of grain are binned together in a terminal elevator, average moisture contents, as estimated from tests on each carlot with a good electrical meter, should provide a sound indication of the storage hazard related to actual moisture content.

All electrical meters, even such meters as the Marconi, for which the grain is ground, are affected by the distribution of moisture within the kernel. Accordingly, meters will give erroneous results for grain that has been recently tempered or rapidly dried. All samples in which the moisture distribution may be abnormal should be stored in airtight containers until equilibrium is established. This generally requires about 8 hours and may take longer.

Readings on all electrical meters are also affected by the temperature of the grain. Accordingly, the temperature of the grain or flour must be known. Unfortunately, it is difficult to measure temperatures of grain samples. Moreover, since the correction for temperature is relatively high (e.g., 0.06% per °F. for the Tag-Heppenstall), any serious

error in measuring the temperature of the sample will lead to an erroneous estimate of moisture content. The United States Department of Agriculture (25a) recommends that the grain temperatures should be allowed to come within 20°F. of room temperature before tests are made. The samples are held in airtight tins provided with a suitable neck to take a rubber stopper and thermometer. If the thermometer is close to the temperature of the grain when inserted, about 5–10 minutes is required before the thermometer indicates the correct temperature of the grain. In the meantime, if the grain is much colder (or hotter) than the room, a gradient is set up in the sample; the outer layers of grain warm up before the center portion surrounding the thermometer. For the Halross meter, an attempt has been made to overcome this difficulty by spreading a thin layer of grain on a flat tray to which a thermometer is attached. A series of these trays is stacked, so that the top tray serves as a cover to prevent moisture loss in the tray beneath. When the moisture result is not required immediately, the safest course is to leave samples in sealed tins until they are within a few degrees of room temperature. For a 1-lb. tin, the time required is about 2 hours for grain at freezing temperature to reach a temperature of 65° in a room at 70°F.

Accurate calibration of electrical moisture meters presents certain difficulties. The best procedure appears to be that of using a large number of samples covering a wide range of natural moisture contents (15, 28, 29). A constant-temperature room in which all samples and the meter can be brought to uniform temperature is almost essential. The regression equation, established as a result of an adequately replicated study of this kind, should prove relatively accurate. Moreover, the data will show the moisture level at which the error of estimate begins to increase substantially. For most meters (29), increasingly less accurate estimates are obtained as the moisture content rises above 17%. The practice of calibrating meters with a few samples, artificially tempered or dried to give an adequate range of moisture levels, does not appear to be satisfactory.

Determination of the temperature correction is equally difficult and also requires an adequately replicated investigation. Moreover, it has been shown (40) that the correction for a given meter is not necessarily uniform over the whole of a reasonable temperature range, nor over the whole of a reasonable moisture range. Some meters, however, do show relatively uniform correction factors.

It is questionable whether all manufacturers of electric meters have undertaken adequate studies in establishing calibration charts and temperature corrections. Moreover, it seems certain that some meters have

gained a poorer reputation than they actually merited because of incorrect calibrations.

Recommended Methods

In this section an attempt is made to summarize recommendations about the use of specified methods for determining moisture contents of specified cereals and cereal products. Recommendations are made by various professional societies and administrative bodies. Among these the Association of Official Agricultural Chemists is probably the most widely recognized, partly because of its rigorous testing procedures and partly because the methods rated "official" are recognized by law as those to be used in enforcing the United States Food and Drugs Act. A number of other societies, including the American Association of Cereal Chemists, give their support to various methods.

Cereals and cereal products are listed in alphabetical order in the first of the three following lists. There are two statements to make about each material: the moisture methods that are recommended and the association recommending them. After each material in the first list are groups of symbols. In each group one symbol is a number and one or more are letters. The numbers refer to the methods given in the second list; and the letters refer to the recommending authorities given in the third list. For example, the symbols 13 AC in the first list indicate that the vacuum-oven method (No. 13 in the list of methods) is recommended for the material by the American Association of Cereal Chemists (A in the list of authorities), and also by the Association of Official Agricultural Chemists (C in the list of authorities).

List of Cereals and Products

barley: 3 C; 7 ADF; 8 F; 13 B.
beans: 7 DF; 8 F.
brewers' grains: 1 B.
buckwheat: 7 DF; 8 F.
cereal adjuncts: 1 BC.
corn, whole: 7 ADF; 8 F; 14 F.
corn, ground: 6 E.
corn gluten feed: 5 E.
corn gluten meal: 6 E.
corn oil meal: 6 E.
corn, sweetened feed: 5 E.
corn steep water: 5 E.
feeds and feeding stuffs: 2 A; 3 C; 6 AC; 13 A.
flaxseed: 7 ADF; 8 F.
flour: 2 AC; 4 A; 13 AC.
grain: 3 C; 6 C; 8 F; 10 C; 12 C.
grains, spent: 1 BC.
hops: 1 C; 6 BC; 11 C.
malt: 1 ABC.
mustard seed: 7 DF.
oats: 7 ADF; 8 F.
peas: 7 DF.
rice: 7 AF; 8 F.
rapeseed: 7 D.
rye: 7 ADF; 8 F.
semolina: 2 A; 4 C; 13 A.
soybeans: 2 F; 3 C; 7 DF; 8 F.
sunflowerseed: 7 DF.
wheat (hard red spring, durum, hard red winter, soft white spring, soft winter): 7 CDF; 8 F.

Moisture Methods

1. Air-oven, 103°–106°C., 3 hours.
2. Air-oven, 130°, 1 hour.
3. Air-oven, 135°, 2 hours.
4. Aluminum plate, 140°, 15 minutes.
5. Bidwell-Sterling, benzene.
6. Bidwell-Sterling, toluene.

7. Brown-Duvel moisture tester.
8. Tag-Heppenstall moisture tester.
9. Two-stage air or vacuum oven as in 2 and 13.
10. Vacuum desiccator, no heat, to constant wt.
11. Vacuum oven 60°, 3 hours.
12. Vacuum oven 95°–100°, 5 hours or constant wt.
13. Vacuum oven 98°–100°, 5 hours or constant wt.
14. Water oven.

RECOMMENDING AUTHORITIES

A. American Association of Cereal Chemists.
B. American Society of Brewing Chemists.
C. Association of Official Agricultural Chemists.
D. Board of Grain Commissioners for Canada.
E. Corn Industries Research Foundation.
F. United States Department of Agriculture.

Note: Bibliography of Standard, Tentative, and Recommended Methods of Analysis of the Society of Public Analysts and Other Analytical Chemists has recently been published in Britain (84).

Comparison of Methods

In practice, the selection of a suitable method of moisture determination will depend upon the specific requirements of the laboratory or industry, cost and availability of equipment, time required to perform a test, the product tested, and the judgment of the analyst. Two further important criteria in moisture testing are the precision and accuracy of the test; the former refers to how closely a result can be reproduced, and the latter to how closely a result represents the actual moisture content of the material tested.

Information on the precision or reproducibility of each of the better-known methods, and the magnitude of sampling errors and of intra- and interlaboratory errors, has been published; interested readers are referred to original publications in assessing the method of their choice (2, 9, 12, 22, 27–30, 35, 36, 65, 69, 81, 83). Most moisture determinations are made for the information of the analyst or his company, hence comparison with results previously obtained in the laboratory is generally adequate.

For comparison with the work of other laboratories, the American Association of Cereal Chemists makes available to its members check samples of flours and feeds which are analyzed by more than one hundred laboratories. Although there is considerable variation, most results agree to within 0.3% and provide a useful interlaboratory comparison of the moisture determination. A similar monthly check test on the determination of moisture in wheat by the Brown-Duvel method is used by the Board of Grain Commissioners for Canada for standardizing equipment and method of testing at various inspection points. The Grain Branch of the Production and Marketing Administration, U.S.D.A., maintains standard Tag-Heppenstall equipment to check their field office equipment, which, in turn, is used for checking and standardiz-

ing the licensed inspectors' equipment. Periodic check tests are made each season.

The accuracy with which any specified method will approach the actual moisture content of the material tested is more difficult to establish than mere reproducibility. In practice, however, two methods are generally adopted arbitrarily as primary standards for the routine laboratory. These are the 130°C. air oven and the 98°–100°C. vacuum-oven methods. The vacuum-oven method gives slightly higher moisture results. The reader is referred to the original references for comparison of the various methods of moisture determination with the air-oven method (13, 22, 24, 60, 61, 68, 69, 78, 87) and with the vacuum-oven method (9, 15, 27–29, 31, 36, 40, 70–75, 82–85). The empirical approach to the selection of a standard or reference method for the determination of moisture in cereal grains and their products only serves to emphasize the need of further basic research in this field.

Primary Reference Methods

The preceding section described various methods which are used for the determination of moisture in cereal grains and their products. Some of these methods are based on the measurement of secondary properties such as electrical conductance and capacitance. Obviously, measurements of secondary properties must be converted into corresponding moisture content values by some basic calibrating procedure. Other methods which were described determine the amount of moisture in grain by distillation, evaporation, or chemical reaction. However, there may be considerable uncertainty about the basic accuracy of the results because of the assumption that no decomposition of the material takes place by these methods, and the essentially arbitrary decision as to when the removal of water is complete. This again emphasizes a need for a basic method, which can determine the actual or "true" water content, and which can be used as a primary reference standard for calibrating other methods. In this concluding section, the progress made in the search for such a basic method of measuring "true" water will be outlined.

The prime difficulties in developing a basic method for the determination appear to be the following. Some water in cereal grains is strongly bound and its complete removal is difficult. Also, the physical properties of cereal materials and the effects of drying are such that the outer portion of each particle is dehydrated and hardened, and becomes much less permeable to the further escape of water remaining in the interior of the particle. This phenomenon is called case hardening. Both these difficulties might normally be overcome by longer heating or higher

temperatures. Unfortunately, cereal products are not entirely stable to heat and some decomposition is to be expected. The search for a basic method of determining true moisture has been concerned with ways of overcoming these and related difficulties. Various approaches have been made with cereals and other materials. These include: drying without heat to avoid decomposition; lyophilization to increase the porosity of the material; the reversibility method to account quantitatively for the amount of decomposition; and finally, the redrying procedure to establish correct drying temperature and time in terms of a primary standard. These and several miscellaneous methods will be discussed in the following subsections. The reader is also referred to excellent reviews of Makower (49), Willits (91), and Fetzer (33).

Drying without Heat. In developing procedures for the estimation of "true" water in cereal grains, an obvious approach is to adopt conditions under which no decomposition takes place. The samples may be dried either without heating, or at moderate temperatures at which no decomposition can be safely presumed. Several procedures of this type are described.

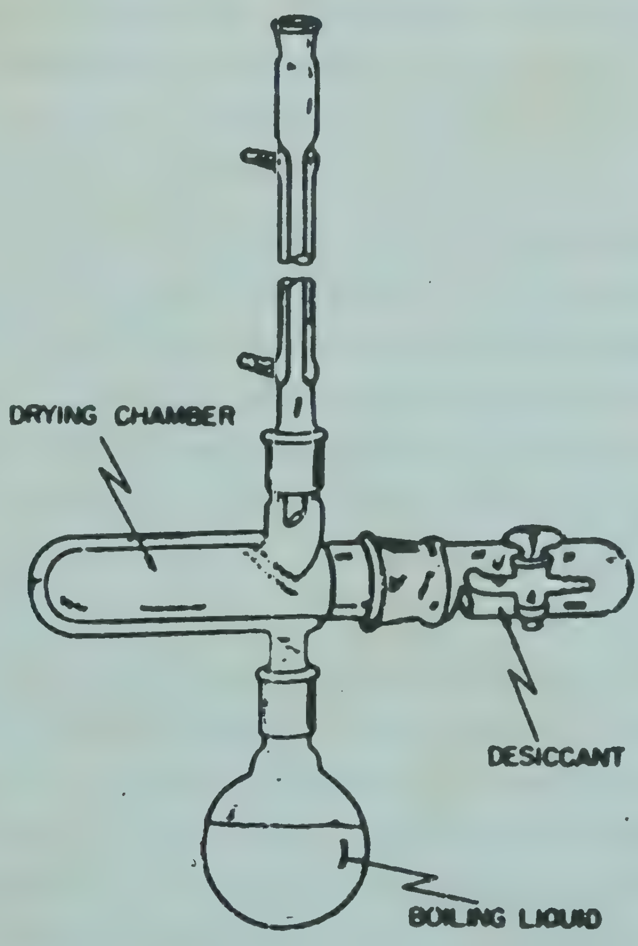


Fig. 6. Abderhalden drying apparatus.

A historically important method of this type is the Abderhalden drying apparatus (Fig. 6). This method employs a vacuum and provides for heating the sample with a solvent of selected boiling point. Phosphorus pentoxide is employed as a desiccant. If it is replaced by a fresh sample toward the end of the drying, the water vapor pressure in

the system is essentially negligible. Birchard (12) who used Abderhalden equipment heated with chloroform (b.p. 61°C.) reported that almost 1,000 hours were required to obtain constant results for flour.

Improved equipment of the De Bruyn type was used by Sair and Fetzer (71) in their classical studies of moisture in corn products. The apparatus consists of two glass flasks joined by glass to a connecting U-tube with a stopcock for evacuation. The sample is placed in one flask and phosphorus pentoxide in the other. Working with De Bruyn equipment, Sair and Fetzer found that at 38°C. it required 600 hours to obtain constant moisture values for ground corn.

The vacuum desiccator, with a suitable desiccant, is also widely used for this purpose. Makower, Chastain, and Nielsen (50) dried vegetable material in a vacuum desiccator with magnesium perchlorate. At room temperature, 6 to 9 months were required to attain constant weight for the products they studied.

In essence, these are the direct primary standard methods for the determination of moisture in biological materials such as cereals. Since the material is not exposed to high temperature, no heat decomposition takes place. Last traces of tenaciously held water are removed by the application of (a) vacuum, (b) efficient desiccant, (c) long period of desiccation, and sometimes by (d) gentle heating. There remains the question of moisture retained in the interior of particles as a result of case hardening. Two aspects are pertinent here, the fineness of grind and the desiccation period. The two-stage drying method should be used, and material should be ground as finely as practicable, as fineness has an important bearing on the rate at which moisture may be removed. The long desiccation period, required to bring samples to constant weight, apparently takes care of the slowness with which moisture diffuses through the drying particle.

Lyophilization. The term lyophilization is applied to the dehydration of frozen substances by sublimation *in vacuo*. This procedure is not in itself a primary method of moisture determination but rather an important aid to other methods. Its usefulness depends upon the fact that when biological material is frozen and lyophilized, the dried material does not collapse but retains its original volume. The mass assumes an extremely fine porous texture. All the moisture is not removed, but drying can be completed by one of the desiccation or oven-drying methods.

The rate of drying of lyophilized material is increased tremendously. Makower and Nielsen (51) showed that with sweet potatoes and white potatoes it was possible to reduce the drying period (vacuum desiccator, magnesium perchlorate, and room temperature) from 6 months to 11

and 4 days, respectively. They attributed the increase in drying rate to two factors. One is the fine texture which is achieved by this treatment, and the other is the increase in porosity which results from leaching of soluble substances in the tissues. So far, the lyophilization procedure has not been applied to the determination of moisture in cereal products

Results of moisture determination on lyophilized materials indicate that the slowness of diffusion of water vapor is one of the basic difficulties in moisture determination by desiccation procedures; high temperature drying and insufficiently fine grinding intensify the difficulty. By the same token it would appear that the role of firmly bound water in preventing complete drying of a material is not as important as is generally believed. Lyophilization provides a promising research tool for improving, shortening, and increasing the certainty of primary methods of determination of moisture.

Reversibility Method. In the primary reference methods for the determination of moisture just described, precautions are taken to avoid loss of matter by heat decomposition. There remains the alternate possibility of quantitatively accounting for the extent of decomposition which may take place. Two such methods have been developed: the reversibility procedure of Sair and Fetzer (71) and the redrying procedure of Makower and Nielsen (51). These will be considered in this and the next subsections.

Sair and Fetzer (71) showed that it was possible to correct moisture results obtained by conventional oven procedures for the effect of heat decomposition. The corrected moisture results then represent "true" moisture. Their procedure was as follows. Portions of the same sample of finely ground corn were dried *in vacuo* at 100°C. for varying periods of time from 2 to 72 hours. These samples were then "rewetted" and excess water was removed *in vacuo* at room temperature. A control sample was given a similar "rewetting" treatment and dried under conditions which permitted the material to retain roughly 1% of moisture. All samples were then repulverized and allowed to reach equilibrium *in vacuo* at 40°C.; this was completely attained in 340 hours. If no loss by decomposition has taken place in the redried test samples during heating, they should have sustained at equilibrium the same loss of weight (expressed as percentage of the original material) as was lost by the control sample.

Results of a typical experiment are given in Table II, which also shows how true moisture is calculated from the data.

Redrying Method. The redrying procedure of Makower and Nielsen (51) is essentially a means of determining the correct drying time, for a given temperature and material, in such a way that loss of weight by

TABLE II

REVERSIBILITY MOISTURE METHOD FOR CORN (71)

	A Apparent Moisture	B Reversible Moisture Value, 340 hrs. at 40°C.	C Adsorption A-B	D Decomposition B-10.41	E Calculated True Moisture A-D
	%	%	%		%
Vacuum oven—40°C.					
340 hrs.	10.41	10.41	. .	. . .	. . . .
Vacuum oven—100°C.					
2 hrs.	11.09	10.39	0.70	. . .	. . . .
4 hrs.	11.48	10.53	0.95	0.12	11.36[a]
16 hrs.	11.82	10.74	1.08	0.33	11.49
22 hrs.	11.90	10.82	1.08	0.41	11.49
48 hrs.	12.06	11.00	1.06	0.59	11.47
72 hrs.	11.98	10.91	1.07	0.50	11.48
				Average	11.48

[a] This value omitted from the average.

heat decomposition is accounted for. A drying curve such as is shown in Figure 7 is first obtained by determining at intervals the loss in weight of a finely ground substance dried in a vacuum oven for 100 hours or more. The sample is then exposed in a humidistat and allowed to absorb water, the amount of which is accurately determined as increase

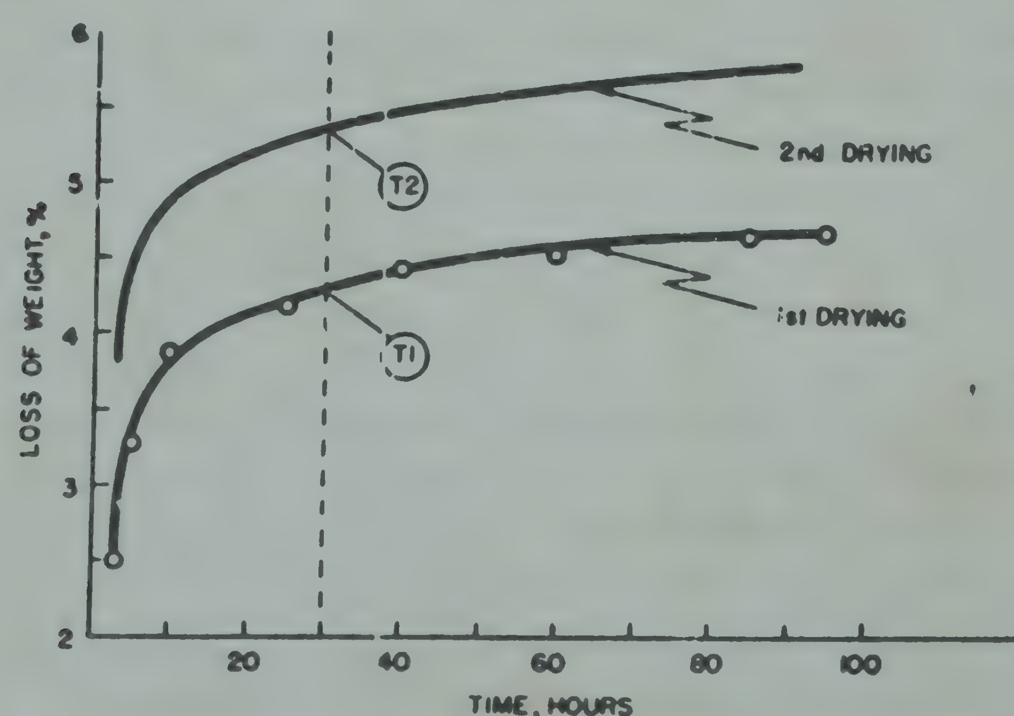


Fig. 7. Drying and redrying curves for carrots (50).

in weight. A second drying curve is then obtained on the same material. The correct drying time is taken as the time which was required to obtain moisture loss equal to the weight of water absorbed in the humidistat.

In Figure 7, the amount of water absorbed in the humidistat by

the sample was 5.3%. In redrying, this moisture loss was obtained in 30 hours, which is taken as the correct drying time T_2 for carrots at 70°C. Referring then to the first drying curve, the correct moisture is taken at T_1 and is 4.3%. The rate of decomposition should be the same during both the first and second drying, i.e., the two drying curves should be superposable. If they are not, a lower drying temperature must be selected.

Other Methods. An interesting primary method for the determination of water was used by Brand and Kassell (14) in their studies on lactoglobulin hydration. It is called the isotopic dilution method. A known amount of heavy water is added to the system, a portion of the total water is then removed, and the content of heavy water in the sample is determined by suitable means. From these data the total amount of water originally present in the sample can be calculated. This method appears to have further possibilities as an independent primary moisture method.

The Bidwell-Sterling distillation method using benzene and toluene was shown by Sair and Fetzer to give true moisture results for corn and corn products. It is likely that this method is applicable to other products as well, but studies are required to establish its validity for each product against an independent primary standard. Fetzer's (33) review should be consulted for the variety of apparatus which has been developed for the distillation methods. It should also be borne in mind that a variety of solvents and especially of azeotropic mixtures is available in addition to those commonly used.

The Karl Fischer titration procedure, described previously, offers an interesting feature. The rapidity with which moisture is extracted with a methanol solvent has been noted by Makower (49). Penetrability of organic tissues by methanol, increased porosity as a result of extraction of soluble substances, and displacement of bound water molecules from adsorption sites may all be factors in increasing the rate of extraction of water. In view of the slow diffusion of water through organic matter, the principle of solvent extraction should find further application whether as an inducement to further study of the Karl Fischer titration or in some other manner.

On the whole, the quest for methods of determining "true" water has been fruitful. There are now several independent primary methods of moisture determination. Most of them are recent developments and have been applied to only a limited number of products and in some instances only principles have been established. Much exacting research lies ahead. But the next stage should be further refinement and intercomparison of independent primary methods of moisture determination.

And with absolute methods established, the rapid routine methods for cereals and other products can then be calibrated in terms of basic methods and used with confidence.

In general summary to this chapter, it may be said that progress in elucidating the ways in which water is held in cereal grains and other products, and in finding methods for accurate moisture determinations, has been desultory. Advances have been made concurrently in widely unrelated areas. Much of the work has remained on an applied or practical level, and fundamental aspects have been slow to emerge. At the present time, however, the status and direction of research on moisture in biological material has been substantially clarified. Both the control chemist and the research chemist may expect significant developments in the future. In the meantime, careful study of the general background is pertinent to a proper appreciation of the subject and to the solution of specific problems.

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Chemical, Physical, and Nutritive Changes During Storage

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Chemical changes, some of which have a profound effect on nutritive values, are continually taking place in all grain and milled products of grain regardless of how they are stored. With very few exceptions these changes tend to be detrimental to the quality of the product. A primary objective in the storage of grain and its products, therefore, should be to control the conditions of storage, wherever practicable, so that the original quality of the products is maintained or the deteriorative changes are minimized. Under the most favorable conditions, grain stored for many years may undergo relatively minor changes in composition and may still be used as a source of nutritious and palatable food or animal feed. Very unfavorable storage conditions, on the other hand, can result in the complete spoilage of the grain for food or feed purposes within a few days.

Factors Influencing Deteriorative Changes

The most important of the known factors influencing the rate of deterioration of grain and grain products in storage are moisture, temperature, oxygen supply, and "condition." These four factors will be discussed individually.

Moisture. Of the various factors influencing the rate of deterioration, moisture is by far the most important. If the moisture content is maintained at a sufficiently low level, grain can be stored for many years with little deterioration even under storage conditions that are otherwise unfavorable. In actual practice, however, grain as it comes from the farm, and milled products of grain as they are normally produced, often have moisture contents near or above the critical levels for safe storage. Moisture levels ordinarily considered safe for the storage of grain and milled products are discussed in Chapter VII and will not be

discussed further here except to emphasize that there are a number of other factors that have an important bearing on the keeping qualities of cereal products. For this reason, it is obviously impossible to state a definite moisture limit below which a given grain or grain product may be stored safely and above which deterioration will occur.

Deterioration in stored grain as a result of excessive moisture may occur, strangely enough, even though the grain when placed in storage is within what is normally considered a safe moisture limit and is uniform in its moisture content. This phenomenon may occur when marked differences in temperature exist or develop in different parts of the storage space. The relative humidity of the interstitial air in the stored grain tends to remain in equilibrium with the moisture in the grain. At any level of relative humidity, however, the actual amount of water vapor per cubic foot of air increases with increasing temperature. The air in the storage space is in constant motion as a result of diffusion or convection. When air from a warm region in the grain reaches a cooler region, it must give up some of its moisture to the grain in order to maintain the proper equilibrium. This interchange of moisture usually takes place entirely in the vapor phase but, in extreme instances, warm air reaching a cold region in the storage space may be cooled below the dew point, and water will be condensed on the cold surfaces of the grain or walls of the bin. Thus moisture is transported from warmer to cooler regions of the stored grain and spoilage as a result of excessive moisture may occur in parts of the storage space, even though none of the grain initially contained sufficient moisture to promote spoilage. The effects of atmospheric changes in temperature on the walls of storage bins, and of heat produced by local pockets of insect infestation, are frequent causes of temperature gradients in stored grain that result first in the translocation of moisture, and then in deteriorative changes resulting from the local accumulation of excessive moisture. The effects of temperature differentials on the movement of moisture in stored grain have been more fully discussed by Anderson, Babbitt, and Meredith (1) and by Oxley (61).

Temperature. The universally recognized fact that foods and other biological materials keep better under refrigeration than at higher temperatures, particularly if they contain an appreciable quantity of moisture, is based on the fundamental fact that the speed of most chemical reactions increases with increasing temperature. Reactions based on enzymatic action, including most of those occurring in living organisms, normally follow this same general pattern under most normal storage conditions (50); but at sufficiently high temperatures inactivation of the enzymes and death of the organisms occur, resulting in a marked re-

tardation of the chemical reactions. Thus grain and its products at moisture levels unsafe for storage at summer temperatures may often be stored safely under artificial refrigeration or at temperatures prevailing in winter. High temperature sterilization to kill all bacteria, fungi, and any other organisms that may be present, and thus to inhibit enzymatic activity, is ordinarily practicable only for products that are to be kept hermetically sealed in order to prevent reinfection with organisms that promote spoilage. Flour intended for baking purposes cannot be sterilized by heat because such a treatment severely affects its baking quality, probably by a denaturing effect on the proteins.

Oxygen Supply. Since aerobic respiration of grain and of the microorganisms associated with grain involves consumption of oxygen and liberation of carbon dioxide, the process tends to be limited by the oxygen supply. In a closed storage space containing grain, therefore, the concentration of carbon dioxide increases, the concentration of oxygen diminishes, and the rate of respiration tends to decrease. An ample supply of oxygen, on the other hand, supports respiration; and if the rate of respiration is high enough, the heat produced in the process will exceed the heat lost and spontaneous heating will occur. These facts should be considered carefully in any plan to aerate stored grain. When heating grain is aerated to reduce its temperature, the beneficial effect obtained may, under some conditions, be more than counteracted by driving out the accumulated carbon dioxide, increasing the oxygen supply, and thus stimulating respiration and further spontaneous heating. If air of low relative humidity is used in the aeration process, however, an additional factor is introduced in that the moisture content of the grain is reduced. This tends to diminish the rate of respiration, and the over-all effect of the aeration process is then more likely to be beneficial. Aerating grain even with dry air, however, may be accompanied by unexpected hazards. If warm, dry air is forced through a bin of cold grain the grain nearest the air intake will dry most rapidly. The air will take up a considerable amount of moisture while it is still warm, and when it is later cooled by the cold grain some of its moisture may be given up. Thus it is at least theoretically possible to increase the moisture content of grain in certain parts of a storage bin by blowing dry air through the grain, even though the moisture content of the grain as a whole is reduced.

Although the view has long been held that grain to remain in good condition in storage must have at least a minimum supply of oxygen in order to "breathe," this view is now subject to considerable doubt (55). In fact, it has been suggested (85) that it may become common practice to store grain in hermetically sealed bins in atmospheres en-

tirely devoid of oxygen. Under these conditions respiration and mold growth would be greatly inhibited, insects and rodents could not survive, and spontaneous heating would not be possible. But even under these conditions deterioration would occur if the moisture content were sufficiently high, principally as the result of fermentation and the activity of anaerobic organisms. Bottomley, Christensen, and Geddes (11a) have shown that certain kinds of molds will continue to grow in damp corn in the almost complete absence of oxygen.

Condition. Respiratory activity and the tendency of grain and its products to deteriorate in storage are considerably influenced by the "condition" or "soundness" of the product. This is one of the major reasons why it is impossible to establish a maximum safe moisture limit for the storage of any grain or grain product. Bailey and Gurjar (5) were the first to demonstrate experimentally that the rate of respiration under controlled conditions of temperature, oxygen supply, and moisture content was distinctly greater for unsound wheat than for sound wheat. It is commonly observed under practical storage conditions that grain containing a high percentage of damaged kernels, or showing other evidences of unsoundness, is much more likely to heat in storage than is sound grain of the same moisture content.

The reasons for this difference in storage behavior between sound and damaged grain do not appear to be completely understood, and have been the subject of considerable speculation. Unsound grain can usually be expected to harbor greater numbers of mold spores and bacteria than sound grain, and since respiratory activity in a mass of grain is believed to be largely that of the microorganisms rather than of the grain itself, unsound grain might be expected to exhibit more rapid respiration than sound grain. Milner and Geddes (57) believe that in damaged grain the nutrients required for the growth of molds at any given moisture level are more readily available to the molds than they are in sound grain, and that mold growth can therefore occur in damaged grain at a lower moisture level.

An interesting speculation in regard to this problem lies in the possible relation between the "bound" and "free" water ratios in sound and damaged grain to the rates of mold growth and respiration. It has been observed repeatedly that the electrical conductivity of unsound grain as measured by conductivity-type electric moisture meters is usually higher than that of sound grain of the same moisture content. The reason for this difference in conductivity is not known, but it seems reasonable to suppose that as grain undergoes deterioration the part of its moisture that is held firmly in close physical union with the proteins and possibly with other constituents of the grain (the "bound"

water) may be released gradually, and thus increase the "free" water content of the grain without changing its total moisture content (as determined by oven drying). If such a release of bound water actually does occur, it would explain the observed increase in electrical conductivity; for grain containing less than 5% of moisture has almost no measurable conductivity, and firmly bound water in grain thus appears to give little, if any, support to the flow of electrical current. It could also explain any greater availability of nutrients for the support of mold growth in unsound grain. Moreover, since the relative humidity of the interstitial air in stored grain presumably depends more closely upon the free moisture than upon the total moisture of the grain, and since the respiratory activity associated with mold growth in turn has been shown to depend largely on the relative humidity of the air surrounding the grain (57), it follows that an increased ratio of free to bound water may explain, at least in part, the more rapid respiration of unsound grain at a given moisture content level and its greater tendency to undergo spontaneous heating. A continuation of this line of reasoning leads to the conclusion that the electrical conductivity of grain may be a better index than its moisture content of its probable storage behavior. Much remains to be learned of the relations that exist among grain condition, the physical states of the moisture, the rate of respiration, and the electrical properties of grain. This subject would appear to offer a fruitful, although perhaps difficult, field for research.

Types of Changes Occurring in Storage

Carbohydrate Changes. Alpha- and beta-amylases attack the starch of grain and grain products during storage, converting it into dextrins and maltose. Amylase activity in wheat has been shown by Popov and Timofeev (63) to increase during the early stages of storage. An increase in the dry weight of grain during storage has sometimes been observed under certain conditions and is explained by Gross (32, 33) by the fact that water is consumed in the reactions involved in the hydrolysis of starch. Thus, the dry weight of the products of starch hydrolysis is greater than that of the original starch. Although this hydrolytic action might be expected to result in a significant increase in the reducing sugar content of the grain, conditions that favor starch decomposition usually favor respiratory activity also, so that the sugars are consumed and converted into carbon dioxide and water. Under these conditions, which usually occur at moisture levels of 15% or more, the grain loses both starch and sugar and the dry weight decreases (18, 35, 43, 52, 53, 91). Leavitt and LeClerc (52), however, showed that the total sugar content of wheat tends to increase during storage. Milner and Geddes

(58) demonstrated a disappearance of sugars in stored heating soybeans during the initial biological phase of the heating process, but a later increase in reducing substances when the heating had reached a nonbiological phase in which the heat produced was the result of direct chemical oxidation. Bottomley, Christensen, and Geddes (11a, 12) have demonstrated a marked disappearance of nonreducing sugars in corn stored under conditions favoring deterioration. Grain resembling spelt, taken from an ancient Egyptian tomb, and said to be more than 3,000 years old, was reported by Geddes (30) to contain dextrins and considerable amounts of reducing sugars. This would appear to indicate that amylase activity continued after the condition of the grain became such that respiration could no longer take place. At higher moisture levels, however, active carbohydrate fermentation may occur with the production of alcohol or acetic acid and resulting characteristic "sour" odors (18).

In the wet milling of corn it has been noted that it is more difficult to obtain a good separation of the starch from the other constituents of the grain when the corn has been stored under unfavorable conditions, even though no apparent damage to the corn can be observed, than when unquestionably sound corn is milled. Experimental wet milling studies reported by Cox, MacMasters, and Rist (16) showed that heat-damaged corn yields only about 45% as much starch as normal corn, that the viscosity of suspensions of the starch in water is very low, and that in many instances the starch granules appear to have split into wedge-shaped fragments.

From a nutritional standpoint it has been reported by Sreenivasan (79) that freshly harvested rice is not digested as readily as rice that has been stored for a time. Fresh rice is said to contain an active alpha-amylase that causes the rice to become sticky when cooked. This amylase presumably becomes partially inactivated during storage.

Protein Changes. Although the total protein content of grain as calculated from its nitrogen content is generally assumed to remain unchanged during storage, Shutt (75, 76) demonstrated a progressive though small increase in the protein content of wheat during extended storage. This increase in protein on a percentage basis is doubtless the result of a loss in carbohydrate by respiration.

A sample of barley taken from an excavation in Asia Minor and claimed to be from 3,000 to 5,000 years old was found in the writer's laboratory to contain 3.2% of nitrogen, equivalent to 20.0% of protein on a moisture-free basis. This compares with an average protein content of modern barley of about 12%. The ancient barley was blackened with age, light in weight, and very fragile, although the character-

istic shape of the kernels was well maintained. It is doubtful if this grain now contains any true protein; the nitrogen is probably present in other forms. The high nitrogen content can probably be accounted for by the fact that the nitrogen-containing compounds were lost more slowly than other constituents of the grain.

Proteolytic enzymes in grain and in organisms associated with grain hydrolyze the proteins into polypeptides and finally into amino acids. These reactions ordinarily proceed very slowly and are not readily measurable until the grain has reached an advanced stage of deterioration (91). Zeleny and Coleman (90) have shown that the free amino acid content of grain may be estimated by an adaptation of the method of Foreman (25) in which the acid phosphates and the free carboxyl groups of the amino acids in a 69% ethanol extract of the fat-extracted meal are determined by titration in 85% ethanol solution. From the titration value thus obtained is substracted the titration value of the acid phosphates alone, which is determined by titration of a similar extract in 5% ethanol solution. The resulting value may be considered an approximate measure of the free amino acid content of the grain, although it does not account quantitatively for any proline or dibasic amino acid that may be present. The amino acid content of corn, measured in this manner and expressed as the number of milligrams of potassium hydroxide required to neutralize the free carboxyl groups in 100 g. of corn on a moisture-free basis, was found usually to be in the neighborhood of 110 mg. in sound mature corn and as high as 320 mg. in severely damaged corn (91).

In a study of the distribution of nitrogen in corn at different stages of maturity, Zeleny (86) has shown that the prolamine (zein) of corn is synthesized very rapidly as the grain approaches maturity and that the rapid increase in the ratio of prolamine nitrogen to total nitrogen is almost exactly paralleled by a rapid decrease in water-soluble nonprotein nitrogen. It appears that the water-soluble nitrogenous compounds are utilized in the synthesis of the prolamine. Similar phenomena probably occur in the maturing of other grains, and it is reasonable to suppose that this rapid change in the ratios of the various grain proteins may continue beyond the time of harvest and into the early period of grain storage, particularly if the grain is not fully matured at harvest. Support for this hypothesis is given by the work of Takahashi and Shirahama (84) who reported that a marked increase in prolamine and a corresponding decrease in water-soluble protein occur in barley during the early period of storage.

Of particular interest is the work of Jones and Gersdorff (39, 40, 41) and of Jones, Divine, and Gersdorff (37) on the changes occurring in

the proteins of various seeds and their ground products during storage. They studied changes in the physical and chemical properties of the proteins and the accompanying changes in protein digestibility. The proteins of wheat, corn, and soybeans, and their ground products, were shown to decrease in solubility and in digestibility by pepsin and trypsin *in vitro*. Simultaneously there occurred an increase in amino nitrogen and a decrease in "true protein" nitrogen. Wheat containing approximately 11% of moisture showed a decrease in protein digestibility of 8% when stored in sealed jars at 76°F. for 2 years. Corn containing about 12% of moisture similarly stored showed a decrease of 3.6% in protein digestibility in the same length of time. These changes, as well as changes in protein solubility, occur much more rapidly in the milled products of grain than in whole grain.

In Tables I, II, and III are shown the protein changes found by Jones and Gersdorff to occur in wheat, whole wheat flour, and white flour in experimental storage.

TABLE I

EFFECT OF STORAGE ON THE PROTEINS OF WHEAT KERNELS (Jones and Gersdorff, 41)
Results Expressed in Milligrams per 100 g. Wheat

Determinations	Fresh Material	Stored in Jars			
		Months at 30°F.		Months at 76°F.	
		9	24	9	24
Moisture	10,950	10,960	10,960	10,950	10,940
Total nitrogen	2,140	2,140	2,140	2,140	2,140
True protein nitrogen	1,682	1,653	1,574	1,632	1,519
Free ammonia nitrogen	37	37	37	38	38
Nitrogen soluble in 3% NaCl	756	620	606	557	516
Nitrogen soluble in 70% alcohol	910	770	748	722	713
Nitrogen soluble in 3% sodium salicylate		1,061	1,038	998	922
Nitrogen in NaCl precipitable by trichloracetic acid	616	518	509	134	163
Nitrogen in sodium salicylate precipitable by trichloracetic acid		943	919	874	788
Amino nitrogen in NaCl extracts	109	102	100	94	88
Nitrogen soluble in peptic-tryptic digests	2,050	2,033	1,987	2,026	1,878

In a continuation of these studies, rats were fed ground corn stored at 76°F. for varying lengths of time. These experiments showed that the product decreased in palatability as well as in nutritive value as the length of the storage period increased.

TABLE II

EFFECT OF STORAGE ON THE PROTEINS OF WHOLE WHEAT FLOUR (Jones and Gersdorff, 41)
Results Expressed in Milligrams per 100 g. Flour

Determinations	Fresh Material	Stored in Closed Jars				Stored in Bags			
		Months at 30°F.		Months at 76°F.		Months at 30°F.		Months at 76°F.	
		7	24	7	24	7	24	7	24
Moisture	10,950	10,960	10,980	10,940	10,960	14,080	14,110	10,490	10,510
Total nitrogen	2,140	2,130	2,130	2,130	2,130	2,130	2,120	2,130	2,140
True protein nitrogen	1,682	1,569	1,507	1,450	1,361	1,534	1,425	1,436	1,285
Free ammonia nitrogen	37	37	37	37	37	36	37	37	38
Nitrogen soluble in 3% NaCl	756	583	550	536	477	573	515	509	428
Nitrogen soluble in 70% alcohol	910	707	689	658	583	686	653	644	538
Nitrogen soluble in 3% sodium salicylate	....	1,019	961	977	894	998	905	956	866
Nitrogen in NaCl extracts precipitable by trichloracetic acid	616	388	326	303	213	371	278	325	138
Nitrogen in sodium salicylate extracts precipitable by trichloracetic acid	....	869	781	795	675	842	709	767	627
Amino nitrogen in NaCl extracts	109	100	109	128	130	111	117	136	137
Digestibility	2,050	2,036	1,887	2,026	1,857	1,954	1,788	1,940	1,751

TABLE III

EFFECT OF STORAGE ON THE PROTEINS OF WHITE FLOUR (Jones and Gersdorff, 41)
Results Expressed in Milligrams per 100 g. Flour

Determinations	Fresh Material	Stored in Closed Jars				Stored in Bags			
		Months at 30°F.		Months at 76°F.		Months at 30°F.		Months at 76°F.	
		7	24	7	24	7	24	7	24
Moisture	12,900	12,900	14,020[a]	12,900	12,990	14,300	14,310	11,300	11,340
Total nitrogen	1,910	1,900	1,890	1,910	1,900	1,900	1,880	1,890	1,890
True protein nitrogen	1,284	1,184	1,069	1,106	989	1,142	1,048	1,086	955
Free ammonia nitrogen	23.5	24.1	24.0	23.7	24.0	24.5	24.0	24.2	23.0
Nitrogen soluble in 3% NaCl	624	410	392	326	268	409	376	305	243
Nitrogen soluble in 70% alcohol	1,026	924	884	812	713	917	861	791	683
Nitrogen soluble in 3% sodium salicylate	....	777	726	725	611	767	687	704	551
Nitrogen in NaCl extracts precipitable by trichloracetic acid	507	273	227	182	97	246	190	148	64
Nitrogen in sodium salicylate extracts precipitable by trichloracetic acid	.	719	651	640	507	695	596	600	437
Amino nitrogen in NaCl extracts	59.6	59.5	67.0	71.4	75.0	61.9	71.0	78.3	83.0
Digestibility	1,894	1,796	1,662	1,760	1,573	1,767	1,631	1,731	1,524

[a] High moisture caused by loosened cover.

This deterioration in nutritive value is assumed to be associated with the changes in protein solubility and digestibility mentioned previously. Similar feeding experiments using whole wheat flour, white flour, and wheat meal showed no significant decrease in nutritive value over a 24-month period. In all these feeding trials the grain and meal were sound and free from any evidence of insect infestation or mold growth throughout the period of the study.

Feeding experiments conducted at the University of Illinois (19) showed that swine fed sound corn made more rapid gains and consumed less feed per day and less feed per 100 pounds of gain in weight than swine fed moldy corn. Whether the deterioration in nutritive value in this case was due to protein changes or to toxic substances resulting from mold growth is not clear.

Fat Changes. Deteriorative changes in grain fats or oils may be either oxidative, resulting in typical rancid flavors and odors, or hydrolytic, resulting in the production of free fatty acids. Grains contain fairly active antioxidants, and the fats in unbroken kernels of grain are rather effectively protected against the effects of the oxygen in the air. For these reasons the development of oxidative rancidity is rarely a problem in grain storage, although it is often a serious problem in the storage of grain oils and of milled products, particularly whole grain milled products. Whole wheat flour, for example, can be kept for only a relatively short time because it readily becomes rancid, regardless of its moisture content.

Fats in grain are readily broken down by lipases into free fatty acids and glycerol during storage, particularly when the temperature and moisture content are high and thus favorable to general deterioration (2, 14, 15, 20, 56, 69, 72, 81, 90, 91). This type of change is greatly accelerated by mold growth because of high lipolytic activity of the molds (30a, 52a). Fat hydrolysis takes place much more rapidly than protein or carbohydrate hydrolysis in stored grain. For this reason, as will be shown later, the free fatty acid content of grain may be used as a sensitive index of incipient grain deterioration.

It has been reported (15a, 54) that lipolytic activity and probably over-all deterioration in grain can be retarded by treating the grain with certain chemicals, particularly ethylene chlorhydrin, propylene oxide, and carbon tetrachloride. At least part of the effectiveness of these chemicals is no doubt due to their inhibitory effect on the growth of molds that are the principal source of the lipases in stored grain. Brief exposure of moist cottonseed to a radio frequency electric field has been found also to markedly reduce lipolytic activity and the liberation of free fatty acids (52b). The heat produced by the electric field appears to

inactivate the lipolytic enzymes, to destroy the molds responsible for these enzymes, and to reduce the moisture content of the seed so that further mold growth is retarded. The above-mentioned treatments, chemical or electrical, have not been used commercially but development along these lines may possibly occur in the future.

Soybeans stored in glass jars for one year at moisture contents in excess of 15% were found by Ramstad and Geddes (64) to show decreases in the iodine numbers of their oils. All of the soybeans stored at these high moisture levels showed considerable mold growth. These observations indicate that the oil from soybeans damaged by storage at high moisture content is likely to have inferior drying quality.

Mineral Changes. Except under very unusual conditions, no appreciable changes normally occur in the mineral content of grain or its products during storage. Moxon and Rhian (60), however, have shown that grain grown on seleniferous soils may lose as much as 73% of its original selenium content during storage. The loss appears to be in the form of volatile selenium compounds, and the rate of loss depends on the type of selenium compounds present and on the temperature of the grain.

It is possible for the percentage of total mineral matter in grain, as measured by the ash content, to increase because of the loss of other constituents. This type of change may be readily measurable in grain that has undergone extensive respiration. An extreme example of this was found in the previously mentioned sample of barley taken from an excavation in Asia Minor and claimed to be from 3,000 to 5,000 years old. Its ash content on a moisture-free basis was 17.2% as compared with a normal barley ash content of about 3%. The barley was black in color, very light in weight, and had obviously lost much of its organic substance.

Although mineral matter is seldom gained or lost in storage, the availability of the element phosphorus, nutritionally important to animals and man, appears to increase on storage. Most of the phosphorus in grain is present in the form of phytin, a calcium-magnesium salt of inositol phosphoric acid. The phosphorus of this compound is not well utilized in the animal body, and about 60% of it is excreted in unchanged form by man (34, 57). During the storage of flour (31) and more slowly in the storage of unmilled grain, phytin is acted upon by the enzyme phytase with the liberation of water-soluble, readily assimilable phosphorus compounds.

Vitamin Changes. Cereal grains and their products are important sources of certain vitamins in food and feed. Losses in vitamin content that may occur during storage are therefore of considerable practical

importance. Unfortunately, relatively little information on this subject is as yet available. Generally speaking, the cereal grains are good sources of thiamine, niacin, pyridoxine, inositol, biotin, and vitamin E. They also contain significant quantities of pantothenic acid and probably para-amino benzoic acid. Vitamin A activity occurs in yellow corn but is practically absent in all other cereal grains (27).

Bayfield and O'Donnell (7) showed that wheat containing about 17% of moisture lost approximately 30% of its thiamine in a 5-month storage period. This wheat deteriorated considerably during this period because of its high moisture content. They also showed that at a normal moisture level of about 12%, the thiamine loss in a 5-month period was in the neighborhood of 12%. The same investigators made thiamine assays on a number of samples of apparently sound wheat of varying ages up to 51 years. No data on the original thiamine content of any of these samples were available for comparison, but the very low values obtained for some of the older samples indicated that considerable loss of thiamine must have occurred. It is interesting to note, however, that some of these samples that were as much as 21 years old still had fairly high thiamine contents and thus appeared to have lost little thiamine during these long periods of storage. Fifield and Robertson (22) reported the thiamine contents of 12 samples of wheat that had been stored in a dry unheated room at Fort Collins, Colorado, for periods ranging from 14 to 21 years. Here again, initial thiamine data were not available, but the relatively high thiamine contents of the stored wheats appear to indicate that the thiamine losses were, in most instances, probably rather small.

Experiments conducted at Iowa State College indicate that the thiamine content of yellow corn stored under ideal farm conditions does not appear to be affected during a period of 4 years (38).

Studies on rice have also indicated that thiamine is quite stable during storage. Hulled rice stored in straw bags for 4 years retained most of its original thiamine content during the first 2 years, but a significant drop occurred during the second 2 years of storage (44). After storage in airtight containers for periods of 26 and 28 years, samples of hulled rice still had thiamine contents of more than half that found in fresh rice (46). Hulled and unhulled rice stored in hermetically sealed concrete bins for 5 years showed no appreciable loss in thiamine (47). Kondō and Okamura (15), however, found that unhulled rice stored at a moisture content of more than 10% suffered appreciable losses in thiamine content and that these losses did not parallel the decrease in viability of the seed.

A few studies have been conducted by commercial flour mills on

vitamin losses in enriched flour.* The results indicate that significant losses of thiamine may occur during storage and that the extent of the losses, although quite variable, depends to a considerable extent on the time and temperature of storage and upon the moisture content of the flour. High temperatures and high moisture contents accelerate the rate of thiamine destruction.

When thiamine chloride hydrochloride is used as an enrichment ingredient, enriched flour may be expected to lose about 10% of its thiamine in 6 months of normal storage, although losses of 20% or more may occur under unfavorable storage conditions. Because of its greater stability, thiamine mononitrate has largely replaced thiamine chloride hydrochloride as a flour-enriching agent. When the mononitrate is thus used, thiamine losses in enriched flour are reduced by one half or more (34a). No appreciable losses of riboflavin or niacin (nicotinic acid) have been found to occur in enriched flour during normal storage.

Very little definite information appears to be available concerning losses of the B vitamins, other than thiamine, found in grain (riboflavin, niacin, pyridoxine, pantothenic acid, para-amino benzoic acid, and inositol). But it is generally believed that these vitamins, with the possible exception of pantothenic acid, are rather stable and are not readily destroyed in unbroken grain under normal conditions of storage. Riboflavin and pyridoxine are rather sensitive to light and may therefore be unstable in milled products exposed to strong light.

The vitamin A activity of yellow corn, although equivalent to only about 3.5 to 5.0 international units per gram, is of considerable importance in animal feeding and may also be of significance in human nutrition in certain sections of the country where corn meal is an important item of the diet. No other grain has any appreciable vitamin A activity. The vitamin A activity of yellow corn is due primarily to its content of beta-carotene, cryptoxanthin, and neocryptoxanthin, and in lesser degree to alpha-carotene and K-carotene (29). These substances are spoken of as "provitamins" and are converted in varying degree into vitamin A in the animal body.

Considerable losses of vitamin A have been shown to occur in yellow corn during storage. Fraps and Kemmerer (28) showed that yellow corn and corn meal may suffer losses in carotenoid pigment even in cold storage; with corn meal as much as 34% of the crude carotene was lost during the first week of storage at 35°C., although subsequent losses were much smaller. Studies conducted at the University of Illinois showed that corn stored in government steel bins in Illinois for 4

* Enriched flour is wheat flour (white flour) containing thiamine, riboflavin, niacin, and iron in amounts specified by the Federal Food and Drug Administration of the United States. The statements on vitamin losses in enriched flour are based on information obtained from General Mills, Inc., and Russell-Miller Milling Company.

years contained less than half the crude carotene of fresh corn (38).

The Bureau of Animal Industry, United States Department of Agriculture, studied corn from the 1937 to 1941 crops that had been stored under government seal in Illinois and Iowa. Chemical and biological assays showed losses of both carotene and vitamin A as the result of storage. In corn over a year old these losses ran as high as 70%. Loss of vitamin A appeared to occur more rapidly during the first year of storage than subsequently.

The disease in cattle known as anasarca appears to be caused by vitamin A deficiency (17, 53a). The disease is manifested by loss of appetite, lameness, marked swelling of subcutaneous tissues, and defective vision, particularly night blindness. Serious economic losses may result from this disease. The apparent relationship between anasarca and vitamin A deficiency lends considerable practical importance to the loss of vitamin A activity in stored yellow corn; however, even diets containing new yellow corn need to be supplemented with roughages of relatively high vitamin A activity, such as alfalfa hay (53a).

Effect of Wheat and Flour Storage on Gluten and Bread-Baking Quality

Bread made from freshly milled flour, unless the flour is treated with artificial aging agents, is ordinarily inferior in volume, grain, and texture to bread made from the same flour after a period of aging. The bread-baking quality of flour normally tends to improve for a period of time depending upon the nature of the flour and the conditions of storage. In the aging process a point is reached beyond which further aging will no longer improve the baking quality. Longer storage will then be accompanied by a gradual decline in bread-baking quality. Since artificial flour-aging agents are usually strong oxidizing agents, it has often been assumed that natural aging is the result of the oxidizing action of the air on some constituent of the flour. Although some improvement in flour color does occur as the result of the bleaching action of air on the carotenoid pigments of the flour, the changes in gluten characteristics that affect the volume, grain, and texture of bread baked from the flour appear to be due primarily to causes other than oxidation.

Kosmin (48, 49) showed rather conclusively that the changes in the physical properties of wet gluten as a result of flour aging are due to increasing amounts of free unsaturated fatty acids in the flour. These fatty acids are formed by the enzymatic hydrolysis of the flour fat. As the flour-aging process progresses, the washed gluten prepared from the flour becomes less extensible and more springy or elastic; finally it becomes

granular and is very easily torn. Kosmin found that removal of the fat from aged flour returned the gluten to its original condition. The addition of this extracted fat, or of oleic acid, to freshly milled flour caused the flour to have gluten characteristics similar to those of the aged flour. Saturated fatty acids, on the other hand, produced no such effects. The effects of free unsaturated fatty acids on gluten behavior reported by Kosmin were confirmed by Sullivan, Near, and Foley (82), Sinclair and McCalla (77), Barton-Wright (6), and Sullivan (80). Although in all instances the presence of free unsaturated fatty acids in flour was shown to have a marked effect on the physical properties of the wet gluten, the effects on the actual bread-baking quality of flour were relatively small. It was shown by Sullivan, Near, and Foley (82) and Sullivan (80), however, that bread-baking quality is adversely affected to a marked degree by the presence of oxidation products of unsaturated fatty acids.

Fisher, Halton, and Carter (23) found that an improvement in the bread-baking quality of freshly milled flour, similar to the improvement produced by artificial aging agents, could be accomplished by the addition of small quantities of very old flour which, because of its age, had become unfit for bread-baking purposes. It seems reasonable to suppose that this improvement may have been due to the high content of free unsaturated fatty acid in the old flour which raised the free unsaturated fatty acid in the blend to the optimum level for gluten development and bread-baking performance. The old flour itself probably contained oxidation products of unsaturated fatty acids in sufficient concentration to render it unfit for bread baking.

The potential bread-baking quality of freshly harvested wheat appears to improve somewhat during storage in a manner similar to that of flour but at a much slower rate. Saunders (66, 67) showed significant increases in the baking strength of flour milled from wheat that had been stored for one year in comparison with flour milled from the same wheat when freshly harvested. The work of Fitz (24) indicated that a considerable part of this change may occur in the very early stages of storage. Saunders, Nichols, and Cowan (68) investigated the baking strength of flour milled periodically from various lots of wheat over a 5-year period. Certain varieties of wheat appeared to increase in baking strength over the entire 5-year period, while other varieties reached their maximum baking strength after 4 years and then receded somewhat in baking quality. More recently Shellenberger (74) has shown, as the result of a carefully planned study, that although the bread-baking quality of wheat does improve during storage after harvest, the extent of the improvement is ordinarily quite small. Presumably, the bread-baking quality of wheat will deteriorate eventually if the

wheat is stored for a long period, but under ideal storage conditions, this deterioration appears to proceed very slowly. Robertson *et al.* (65) and Fifield and Robertson (22) reported that very satisfactory bread was made from flour milled from wheat stored for 9 to 22 years under nearly ideal storage conditions at Fort Collins, Colorado, and that the baking quality did not change appreciably during the last 5 years of storage. No data were available, however, on the initial baking quality of these lots of wheat.

The experience of commercial flour millers leads to the belief that in certain years the potential baking quality of freshly harvested wheat improves only slightly during an initial storage period, while in other years the improvement may be quite marked. Commercial millers also generally believe that wheat should be milled before it is more than a year old to avoid possible deterioration in baking quality, although in the colder parts of the United States storage for a considerably longer period is considered fairly safe.

Indexes of Deterioration

Physical Indexes of Deterioration. There are physical indexes of the deterioration of grain in storage which can be measured by tests commonly used in practical grain inspection. These indexes are general appearance, temperature, odor, damaged kernels, and injurious insects.

When grain deteriorates in storage, especially when the deterioration is caused by spontaneous heating, the grain loses its natural luster and becomes rather dull and lifeless in appearance. This unnatural appearance is an indication that other physical indexes of deterioration may be present in the grain, and the grain should be examined closely to detect any of them. General appearance alone, as an index of deterioration, is considered as a quality factor in the routine inspection and grading of barley, oats, grain sorghums, and soybeans. The general appearance of any type of grain reflects to some extent the degree of soundness of the grain.

High temperatures in grain, which are the result of spontaneous heating, are caused primarily by the growth of molds, and this condition occurs when the stored grain contains excessive moisture. The presence of insects in large numbers may also cause grain to heat. The temperature of grain may be determined accurately by the use of thermometers or thermocouples and roughly by feeling the grain with the hands. High temperature in grain, if it results from spontaneous heating, is a positive indication of deterioration, and even a slight rise in temperature above what is considered normal under prevailing condi-

tions may indicate incipient deterioration.

Abnormal odors, such as musty or sour odors, are usually associated with grain that is heating or that is badly deteriorated. Sour odors are present in grain that has undergone fermentation. Musty odors in grain are usually caused by the growth of certain molds. Grain may possess a musty or sour odor in the early stages of deterioration, but these odors usually occur only when the grain has reached a fairly advanced stage of deterioration. Musty odors in wheat frequently carry through into the flour and the bread or other baked products made from it.

Kernels with damaged germs, usually caused by mold growth or spontaneous heating, heat-damaged, and sprout-damaged kernels all indicate distinct deterioration in grain. These types of damaged kernels occur frequently in stored grain which contains excessive moisture and which is not aerated and handled properly to prevent deterioration. Germ-damaged kernels can be identified by the brown to black discoloration of the germ or embryo of the affected kernels. Wheat damaged in this manner is frequently referred to as "sick" wheat. Kernels of grain that are damaged by heat to the extent that the germs and portions of the endosperms of the kernels are materially discolored (dark red to mahogany) are considered by grain inspectors as heat-damaged kernels. Sprouted kernels can be easily identified by the presence of attached sprouts, or by evidence of the germ end of the kernels having been broken open from germination. This condition is distinguishable in the early stages of germination and also after the sprout has emerged and has been broken off the kernel.

The large part of damage to grain that is caused by injurious insects occurs while the grain is in storage. Sufficient heat may be generated by their respiration to produce heating of the grain. Kernels of grain which contain dead insects, insect fragments, and insect refuse, and kernels of wheat, rye, barley, and grain sorghums which contain insect-bored holes are considered by grain inspectors as damaged kernels. The mere presence of injurious insects in stored grain is considered an index of deterioration. A discussion of insects in stored grain is covered more fully in Chapter V.

The above-mentioned physical indexes of the deterioration of grain in storage can be detected in their early stages of development by careful observation. If the contributing causes are eliminated, deterioration will cease or be greatly diminished. If grain is stored properly and turned, aerated, or dried when necessary, deterioration as indicated by these physical characteristics will be prevented.

Acidity Measurements as Indexes of Deterioration. It has long been known that deterioration in grain and milled products of grain in

storage is accompanied by an increase in acidity. Hydrogen-ion concentration tends to increase with age (73, 78), but because of the buffer action of the proteins and other constituents of the grain, marked changes in hydrogen-ion concentration ordinarily do not occur until deterioration is fairly well advanced. Titratable acidity, on the other hand, is likely to increase significantly even in the very early stages of deterioration.

Many methods have been proposed for determining the titratable acidity of grain and its milled products. The most prominent of these are summarized as follows:

(1) *The Besley and Baston Method.* This method (8, 9, 10) for determining the acidity of corn is essentially an adaptation of the method of Black and Alsberg (11) and consists of digesting the meal with 80% alcohol, filtering, diluting an aliquot of the filtrate with water, and titrating the acid with standard alkali, using phenolphthalein as an indicator. Results are expressed as the number of milliliters of normal potassium hydroxide required to neutralize the acidity of 1,000 g. of corn.

(2) *The Greek or Balland Method.* This method, described by Brooke (13) and by Fifield and Bailey (21), was adopted by the Greek government as its official method for determining the acidity of flour. The flour is extracted with 85% alcohol; the extract is filtered, and the filtrate is titrated with alcoholic potash, using curcuma as an indicator. Results are expressed as per cent sulfuric acid. A later modification of this method was proposed by Panopoulos and Megalooikonomos (62).

(3) *Schulerud's Method.* The flour is digested with 57% alcohol and the filtrate is titrated with standard alkali, using phenolphthalein. Results are expressed as milliliters of normal alkali required to neutralize the acid from 100 g. of flour (70, 71).

(4) *The Former A. O. A. C. Tentative Method.* This method (3), intended for flour, consists in digesting the flour for 1 hour at 40°C. with water and titrating the filtered extract with standard alkali using phenolphthalein as an indicator. Acidity is reported as per cent lactic acid.

(5) *Methods Based on Determination of Free Fatty Acids.* Methods based on the determination of the free fatty acids in grain and flour have been proposed by Coleman (15), Johnson and Green (36), Swanson (83), Zeleny (89, and 4—the present A.O.A.C. official method), and Secchi (72). The procedures used and the methods of expressing the results differ appreciably, but all of these methods consist fundamentally in extracting the fats and free fatty

acids with a suitable solvent and determining the free fatty acid content either of a definite weight of the extracted material or of the material extracted from a definite weight of the original grain or flour.

Of the many methods that have been proposed for determining titratable acidity, most not only fail to yield concordant results but generally fail to yield results that are even approximately proportional to one another. In a critical study of this problem, Zeleny and Coleman (90) showed that the acids present in grain consist primarily of: (a) free fatty acids produced by the action of lipases on fats; (b) acid phosphates produced by the action of phytase on phytin; and (c) amino acids produced by the action of proteolytic enzymes on protein. Methods were devised for determining these three classes of acidic substances independently, and these methods were used to demonstrate the relative rates at which the different classes of acids increase as grain deteriorates.

Acidity values and other indexes of deterioration were determined periodically in wheat stored in two experimental bins at Hays, Kansas. The wheat had sufficiently high moisture content to deteriorate rather rapidly. The changes on a percentage basis that occurred in acidity and germination are presented graphically in Figures 1 and 2. It is obvious from these data that the fat acidity, the phosphate acidity, and the total titratable acidity increased as the wheat deteriorated in storage and that the viability of the wheat decreased in a somewhat parallel manner.

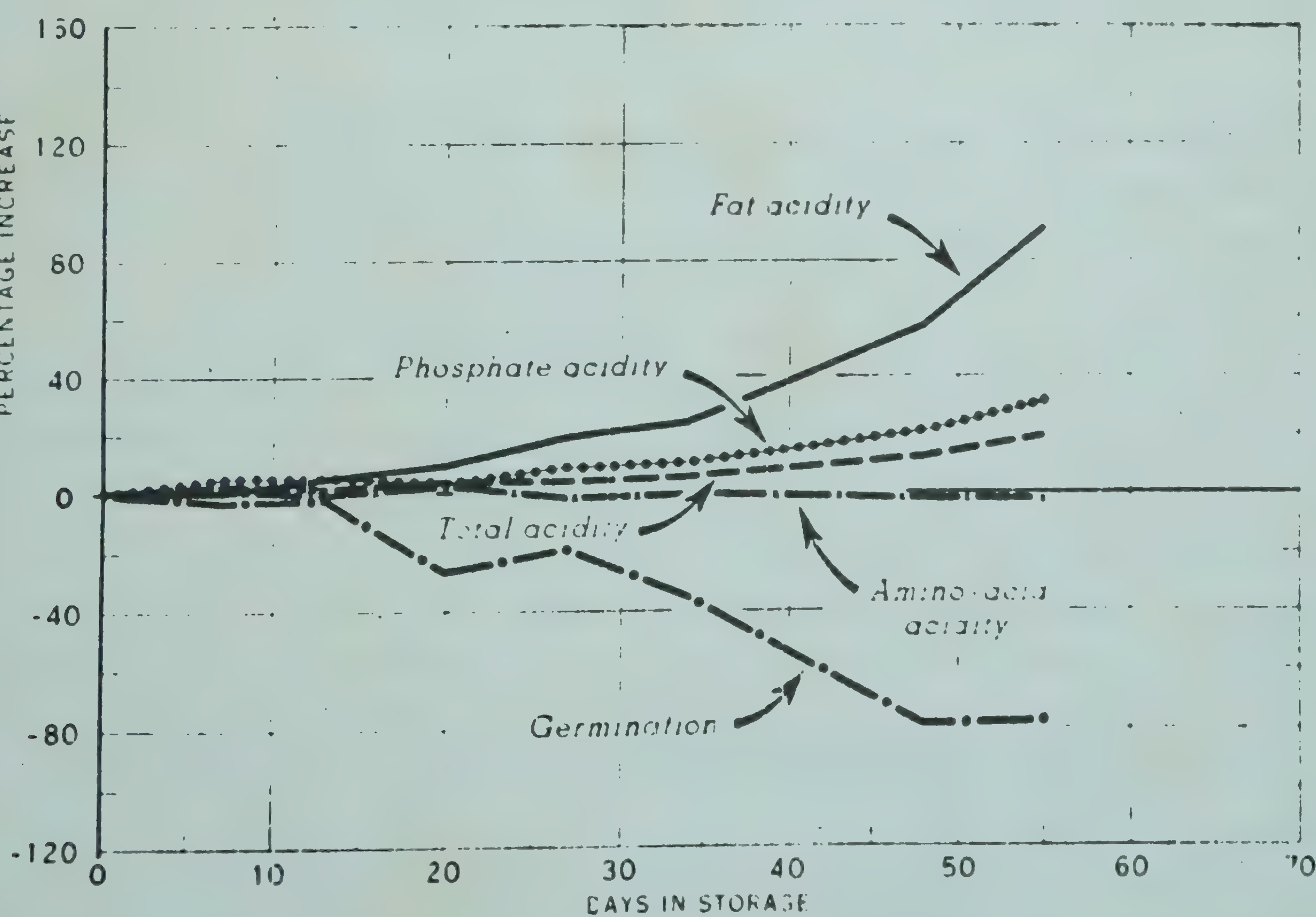

Fig. 1. Percentage changes in acidity values and germination of hard red winter wheat, stored at 14.45% moisture at Hays, Kansas (Zeleny and Coleman, 90).

The amino acid acidity showed no increase during the periods of storage studied. It is also apparent that the rate of increase in fat acidity was greater than that of the phosphate acidity, particularly during the early stages of deterioration.

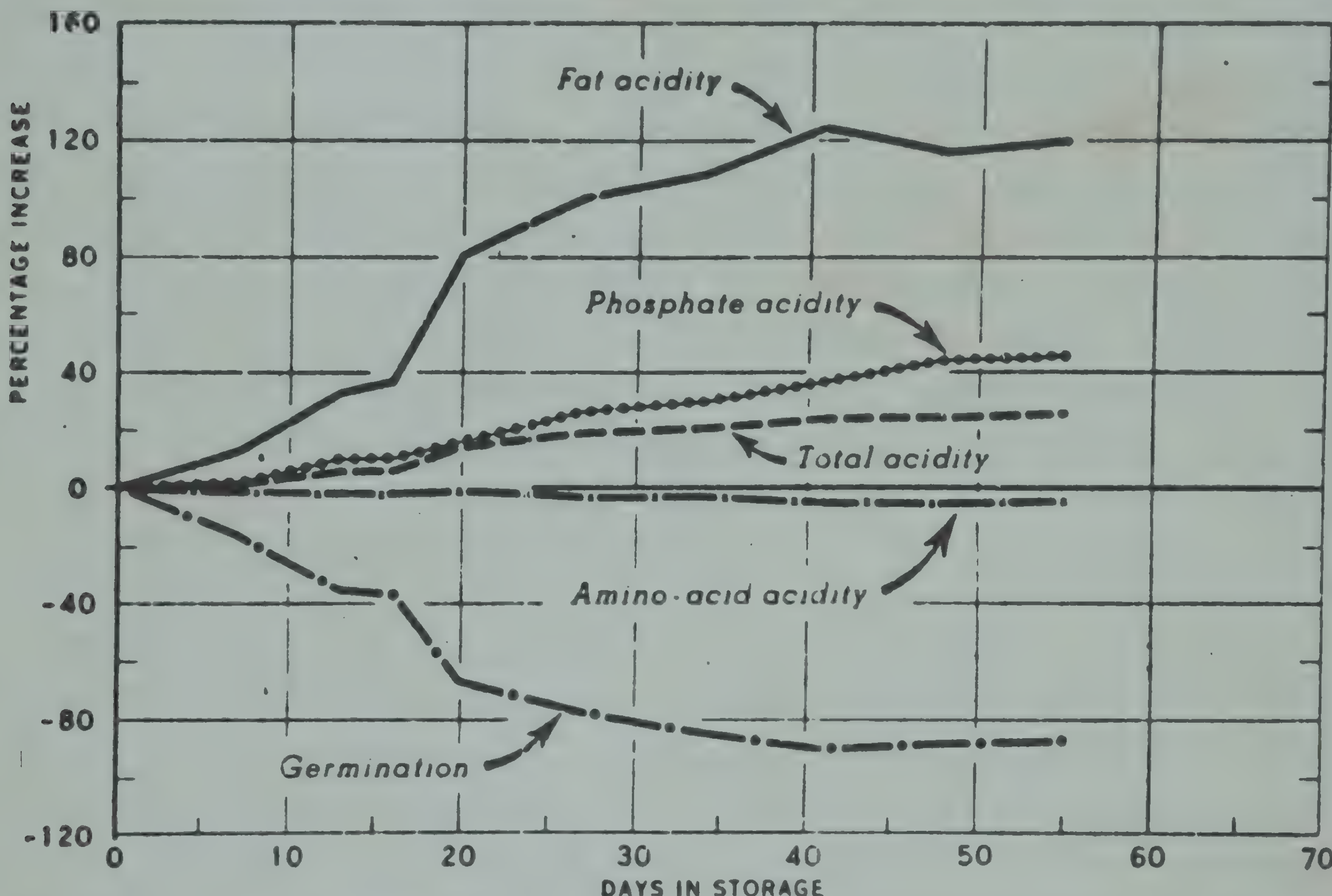

Fig. 2. Percentage change in acidity values and germination of hard red winter wheat, stored at 15.35% moisture at Hays, Kansas (Zeleny and Coleman, 90).

Studies were also made of the acids present in 252 samples of corn classified according to the percentage of "damaged kernels" and of 209 samples of corn classified according to viability. The data obtained are shown graphically in Figures 3 and 4.

These data for corn show that, with increasing deterioration as measured both by grade and by germination, fat acidity increases at a much greater relative rate than does either of the other types of acidity, or all types of acidity combined (total acidity). It should also be noted that a significant increase in phosphate acidity occurs only in corn that has undergone considerable deterioration, and that amino acids increase only when the deterioration is well advanced. On the other hand, highly significant increases in fat acidity appear at very early stages of deterioration. It thus appears that, of the three types of acidity under consideration, the free fatty acid acidity alone may be used as an index of incipient deterioration. The correlation coefficient between fat acidity and percentage of damaged kernels (as determined for grading purposes) for the 245 samples was +0.90, and the correlation coefficient

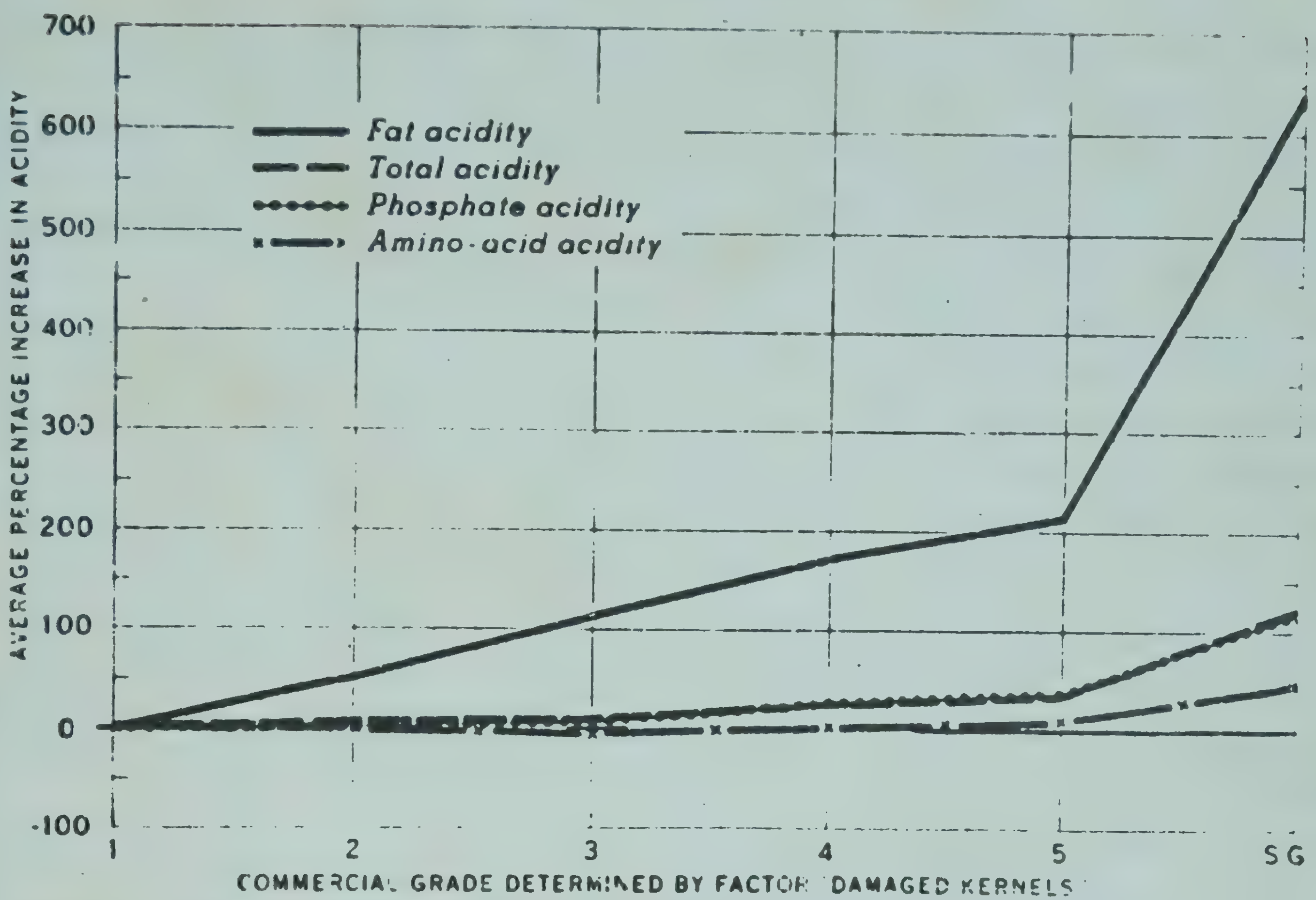

Fig. 3. Average percentage increase in acidity values of corn corresponding with lowering commercial grade (Zeleny and Coleman, 90).

between fat acidity and the logarithm of the percentage germination for the 209 samples was —0.85.

Fat acidity is defined as the number of milligrams of potassium hy-

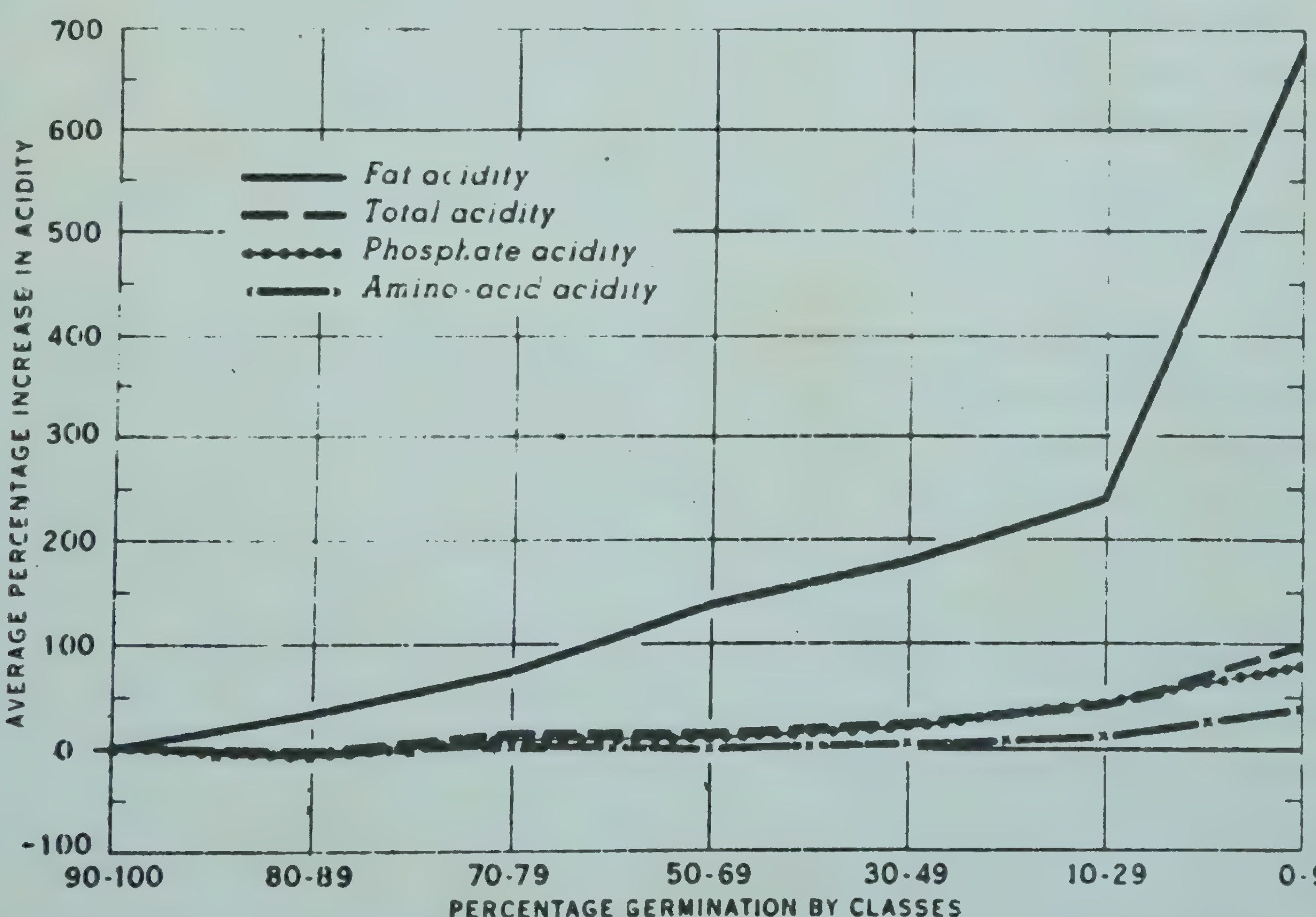

Fig. 4. Average percentage increase in acidity values of corn corresponding with decreasing viability (Zeleny and Coleman, 90).

droxide required to neutralize the free fatty acids from 100 g of grain (moisture-free basis). The test is performed by extracting the fats and fatty acids from a weighed portion of freshly ground grain with petroleum ether or benzene, and determining the free fatty acid content by titration of the extract dissolved in equal parts by volume of benzene and ethyl alcohol. Starting with the original product to be tested, fat acidity as thus defined may be determined more quickly and simply than can the acid value or the free fatty acid content (in terms of oleic acid) of the extracted fat. Moreover, there is evidence to indicate that the fat acidity method of expressing free fatty acid content constitutes a more reliable index of soundness than other methods of expression. Freshly harvested wheat and corn of unquestionable soundness usually have fat acidity values between 10 and 20. These values increase exceedingly slowly under the most favorable conditions of storage but very rapidly under adverse storage conditions. Severely deteriorated wheat may attain fat acidity values as high as 110 and corn as high as 250.

High fat acidity values have been shown to be associated with high content of damaged kernels (42, 91), the presence of "sick" wheat (14, 56), low viability (42, 91), and poor bread-baking quality (87). The development of undesirable flavors in rolled oats has also been shown to be associated with a high content of free fatty acids (59a).

In an extensive study of the behavior of wheat stored in experimental farm-type bins, Kelly, Stahl, Salmon, and Black (42) showed that, ordinarily, fat acidity values increased and viability decreased significantly long before external physical evidence of wheat deterioration appeared. Holman and Carter (34b), in a somewhat similar study of soybeans stored in farm-type bins, showed that at various moisture content levels, losses in viability were closely paralleled by increases in fat acidity.

Since it frequently has been noted that unsound grain tends to heat more readily than sound grain stored under similar conditions, controlled experiments have been performed on a laboratory scale to determine whether or not the degree of soundness as measured by the fat acidity test would be of any value as a supplementary index of storage behavior (88). Samples of commercial corn covering wide ranges in both moisture content and fat acidity values were placed in one-quart vacuum bottles and the bottles were placed in an incubator held at 90°F. Temperature readings were taken of the corn in each bottle at frequent intervals in order to determine the rate at which each sample underwent spontaneous heating as a result of respiration. The results indicated clearly that, at any given moisture-content level, the tendency of the corn to heat increased with increasing initial fat acidity. Thus

it was shown that the rate at which corn would heat in this experimental type of storage could ordinarily be predicted more accurately from a knowledge of both the moisture content and the fat acidity value than from a knowledge of the moisture content alone.

Figure 5 shows the relationships among fat acidity, moisture content, and rate of heating that occurred under the experimental conditions used. The curves in this figure show that at 15% of moisture, corn with a fat acidity of 20 or less would not be expected to show any appreciable spontaneous heating, but that corn with a fat acidity of 100 would be expected to show an average rise of 2°F. in temperature per 24 hours. Likewise, corn containing 20% of moisture would be expected to show an average rise of only 2°F. in temperature per 24 hours if the fat acidity is 20, but if the fat acidity is 100 the predicted rise in temperature in 24 hours would be nearly 14°F.

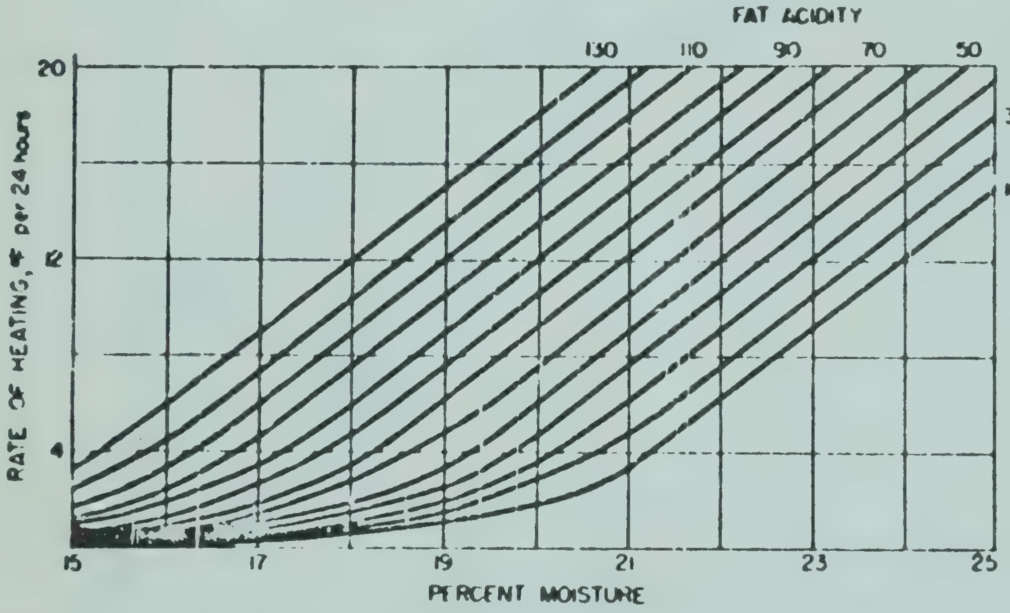

Fig. 5. Relationships among moisture content, fat acidity, and rate of heating for corn in experimental storage (Zeleny, 88).

It should be emphasized that the curves in Figure 5 may be used for predicting rates of heating only for corn in experimental storage under a given set of conditions; it is improbable that the same curves can be applied to corn or other grains in commercial storage. It is reasonable to expect, however, that under any normal storage condition, either commercial or experimental, analogous relationships will hold, and that the fat acidity value should prove to be a useful tool for evaluating grain in terms of anticipated storage behavior.

Information obtained from practical studies of grain in commercial storage indicates that, although fat acidity values may be very helpful in predicting the storage behavior of grain, other factors, as yet unknown, also have a marked influence on the tendency of grain to heat and deteriorate. Different lots of sound grain of uniformly low fat acid-

ity and of the same moisture content often show marked differences in their tendency to heat in storage. The types and quantities of fungi and bacteria present may account in part for these differences. Much more research needs to be done before it becomes possible to predict in advance the storage behavior of grain with a high degree of accuracy.

Disappearance of Nonreducing Sugars as an Index of Deterioration. In studying the influence of physical factors on biochemical changes in stored corn, Bottomley, Christensen, and Geddes (11a, 12) demonstrated

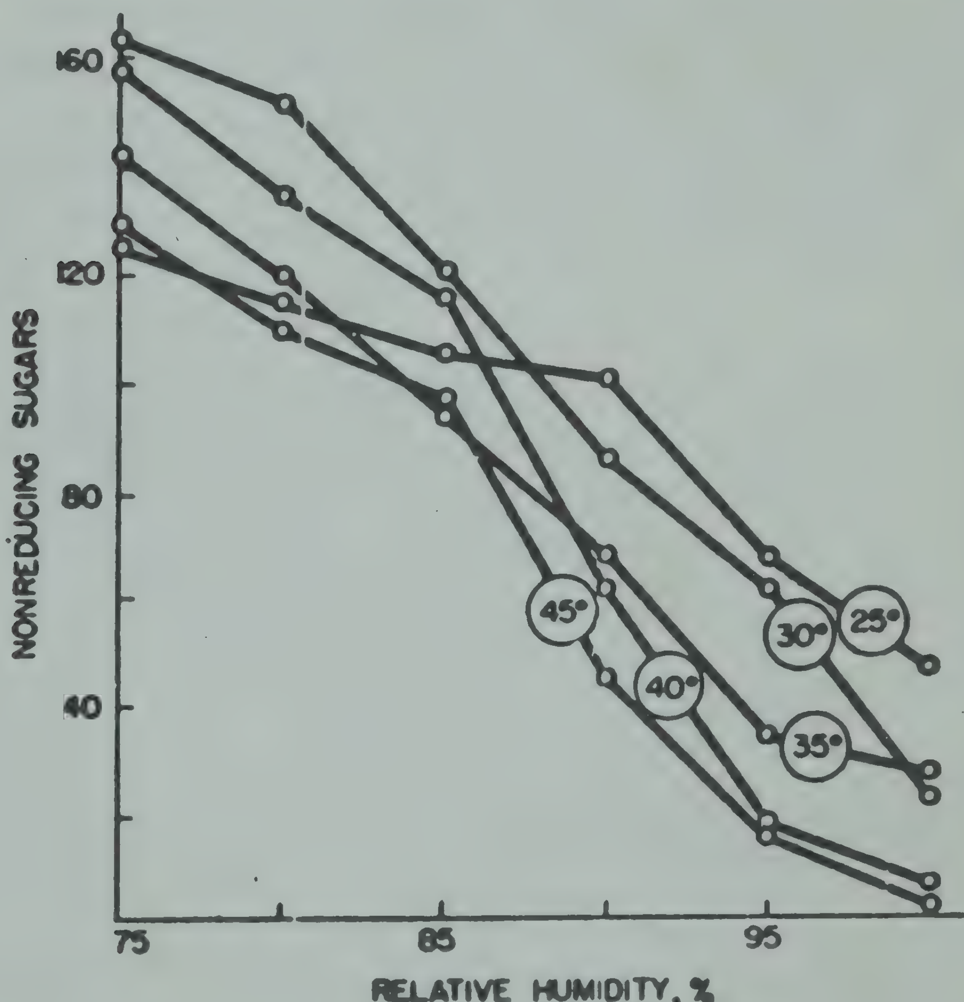

Fig. 6. Effect of temperature (°C.) and relative humidity on the mean nonreducing sugar content of corn stored 12 days under five atmospheres (0.1–21% oxygen). Nonreducing sugars are expressed as mg. sucrose per 10 g. corn, dry basis (Bottomley, Christensen, and Geddes, 11a).

a marked disappearance of nonreducing sugars in corn stored at high moisture levels. The nonreducing sugars are converted into reducing sugars by the action of invertase or similar enzymes, the source of which is probably the various molds that develop rapidly at atmospheric relative humidities of 75% and over. Figure 6 shows the fall in the nonreducing sugar content of corn with increasing relative humidity after 12 days of storage at five different temperatures. Figure 7 shows the relationship between the number of viable mold spores in the corn and the content of nonreducing sugars.

There appears to be good evidence that the activity of the enzymes

that split nonreducing sugars is less variable than the activity of fat-splitting enzymes among different kinds of molds. The nonreducing sugar content of corn, and possibly other grains, may therefore be a better index of the degree of moldiness, and perhaps of over-all deterioration, than the fat acidity of the grain. In the data obtained by Bottomley, Christensen, and Geddes the nonreducing sugar content of corn dropped from initial values as high as 174 mg. of sugar (as sucrose) per 10 g. to as low as zero for badly deteriorated corn.

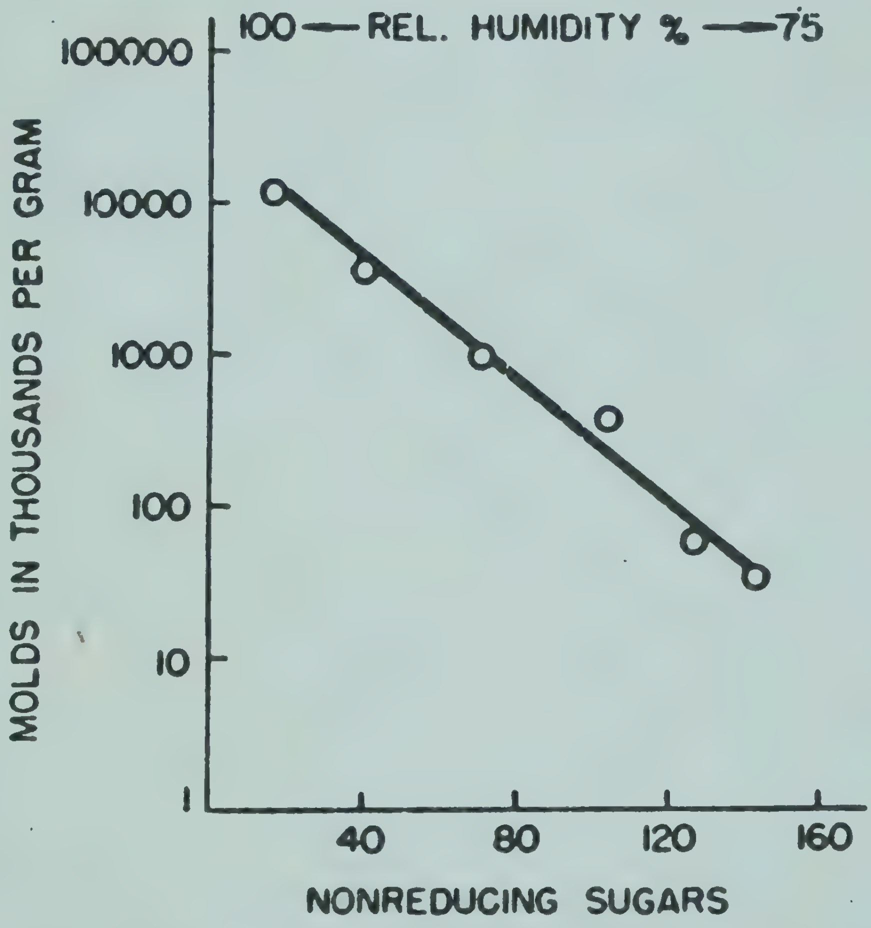

Fig. 7. Relation between mold count (plotted on a logarithmic scale) and nonreducing sugar content of corn stored under relative humidities of 75 to 100%. Each point represents the mean of 25 values; that is, for corn samples stored at each of five temperatures (25°–45°C.) and five atmospheres (0–21% oxygen). Nonreducing sugars are expressed as mg. sucrose per 10 g. corn, dry basis (Bottomley, Christensen, and Geddes, 11a).

Utilization of Storage-Damaged Grain and Grain Products

Grain and its milled products that have undergone fermentation or serious spontaneous heating, or that have become musty, moldy, infested with insects or rodents, or otherwise materially damaged in storage, are ordinarily considered unsuitable for use as human food. Unfortunately, considerable quantities of unsound grain do find their way into human food as a result of the common but questionable practice of mixing unsound grain with sound grain in such proportion that the final mixture is of acceptable quality.

Unsound grain and milled products are most widely used for animal feed. If their quality is not too bad, such cereals may be fed directly, or may be mixed with better quality products. Although the feeding of unsound grain is generally considered an acceptable practice, it should be remembered that such grain is likely to be inferior to sound grain in its nutritive quality and that in some instances damaged grain or damaged milled products of grain may be toxic.

Horses and sheep should not be fed unsound products. Horses are particularly sensitive to the toxic principles that may be present in damaged grain, and sheep will frequently refuse to eat such products. Poultry are usually less susceptible than horses and sheep to any injurious effects of eating unsound grain, and cattle and swine are still less likely to be adversely affected by such a diet. Grains or their products infested with the fungus *Gibberella* are highly toxic to all livestock and should never be used for food or animal feed. Animals eating products infested with this fungus are likely to be poisoned fatally (26, 59).

Grain and milled products that have deteriorated to such an extent that they are not suitable for use as feed can be used for the production of commercial alcohol. The yield of ethyl alcohol obtained from such products is comparable with that obtained from sound products unless the deterioration has progressed to such a point that a significant amount of the carbohydrates has been destroyed.

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Microflora

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The microflora of cereal grains and cereal products is made up of a wide variety of fungi and bacteria, including actinomycetes. These microorganisms are the same as those found in soil and air, and on or in living or dead plants and animals. According to conservative estimates their activities result in the loss of between 1% and 2% of the world's grain production (188), while the threat of their activities causes even greater waste in added costs for drying and storing and in penalties inflicted by untimely marketing and lower commercial grading.

Fungi and bacteria are usually present in grain and grain products. Their kind and abundance depend on such factors as the climate under which the grains are produced, the conditions of storage, and the portions of the grains of which the products are composed. The relation of microorganisms to such changes in stored grain and grain products as spontaneous heating, the development of off-odors, and various types of kernel discolorations is now generally accepted, although the exact nature of their role is not always clear. To provide a basis for a better understanding of the parts they play, the present chapter supplies information as to: (a) the kinds and abundance of fungi, bacteria, and actinomycetes found in wheat, oats, barley, rye, corn (maize), flour, bran, and grain meals; (b) the effects of temperature, moisture, and oxygen supply on the growth of these microorganisms; (c) the influence of storage conditions upon their activities; (d) the effect of microorganisms on the quality of grain and grain products; and (e) methods that may be used to control their activity. The literature on this topic is large and unassembled, and since biological behavior is dependent on many factors beyond those that are seemingly controlled, the problem of summarizing available information necessitates detailed citation of individual observations.

Characterization of the Microflora

Fungi, bacteria, and actinomycetes are morphologically simple micro-

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organisms that are classified in the division Thallophyta of the plant kingdom. They comprise many types of which most or all those found in grain and grain products are heterotrophs, requiring organic materials for growth. They include plant parasites and saprophytes, and their diversity of type makes growth of one or another of them possible over a wide range of environmental and nutritional conditions.

Fungi. Fungi are formally classified on reproductive and morphologic features as Phycomycetes, Ascomycetes, Basidiomycetes, Fungi Imperfecti, or Mycelia Sterilia in the phylum Fungi (86, 227). They are commonly divided on morphology of growth into molds, yeasts, and yeastlike fungi (356), which cuts into the formal system of classification.

Molds develop thin-walled tubes, called hyphae, that become filamentous, branched, and interconnected into a three-dimensional network of mycelium. Their protoplasm is youngest and most active at the hyphal tips where growth becomes manifest in an apical elongation of these tips (323), behind which are formed cross-walls, branches, and reproductive structures. Cross-walls without central pores are formed late in Phycomycetes, while cross-walls with central pores are formed early in the hyphae of Ascomycetes, Basidiomycetes, Fungi Imperfecti, and Mycelia Sterilia (64, 227). The pores remain open in the regions where the protoplasm is growing and become plugged in the region where growth stops or where adjacent cells are injured. The pores are plugged in the production of hyphal fragments, aggregated hyphae (sclerotia), or spores, which serve to perpetuate and disseminate the fungi.

Spores, which may be unicellular or multicellular and of various shapes, are recognized as gemmae, chlamydospores, conidia, sporangiospores, zygospores, ascospores, and basidiospores. They vary in the length of time they are viable and thus they are not equally effective in perpetuating or disseminating the fungus. In a favorable environment, viable spores germinate to produce one or more hyphae, which invade and colonize grain and grain products. The hyphae advance into the substrates by enzymological and mechanical action, their progress being affected by the availability of nutrients and by moisture, temperature, and aeration. Toxic substances, other microbes, and mechanical obstructions hinder or prevent their advance.

Yeasts and yeastlike fungi, which are classified among Ascomycetes and Fungi Imperfecti (98, 244, 282, 356, 370), develop separate cells that either increase in number by budding or fission, or develop mycelium or pseudomycelium. Mycelial forms multiply by budding yeastlike cells (blastospores), by disarticulating oidia (arthrospores), or by forming conidia. Pseudomycelial forms develop chains of elongated budded cells.

Bacteria. Bacteria are classified in five orders of the class Schizo-

mycetes, phylum Schizophyta (58),* but only those of the orders Eubacteriales and Actinomycetales have been studied in grain and grain products. Eubacteria consist of independent cells that are either spheres or rods (0.2 μ to 4.0 μ in greatest dimension), motile or nonmotile, single in chains, or in groups. They are classified into 13 families, only seven of which are represented in grain and grain products. Their cells increase by fission and because these are independent of one another, they are incapable of mechanically penetrating intact cereal grain tissues, but enter through rotted tissues, natural openings, or insect wounds. They are held to plant surfaces by the gumlike substances they produce and survive thereon as encapsulated cells or endospores.

Actinomycetes, which are classified in the families Mycobacteriaceae, Actinomycetaceae, and Streptomycetaceae, produce elongated branched cells or a mycelium of narrow, branched, septate hyphae, mostly less than 1 μ in diameter. The mycelium is short-lived and divides by segmentation into bacillary or coccoid elements in the family Actinomycetaceae, while in the family Streptomycetaceae it persists.

Microflora of Cereal Grains

Microorganisms are carried on, in, and with the grain, and are more abundant on the outside than the inside of the grain. They are here divided into internal and external microflora.

Internal Microflora

Parasites and saprophytes comprise the internal microflora. Both are prevalent in grain produced in warm, humid, and semihumid areas of the world where periods of frequent intermittent rainfall, high relative humidity, dews, and high temperature favor infestation during grain development and maturation.

Microorganisms within grains may be detected: (a) by noting their growth from surface-disinfected whole grain stored moist or planted on laboratory culture media; (b) by observing their infection of seedlings or older plants grown from the grain; (c) by detecting them microscopically in grain tissue; and (d) by examining grain for shrivelled or mummified kernels, discolored embryos, scutella, endosperms or pericarps, bacterial crusts, fungus mycelia, or fungus-fruiting structures (262, 354). Internally carried *Ustilago nuda* of barley, *U. tritici* of wheat, and *Helminthosporium gramineum* of barley are usually discovered by the second or third method (331), while the first method is generally used for the detection of other parasites. Detection by the first method is usually accomplished by surface-disinfecting the grain in a mercuric chloride solution for as long as 10 minutes, rinsing in sterile water, and plating

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* Recent cytological studies of bacterial life histories point to revisions in the system of bacterial classification (36).

on an agar medium (Fig. 1). The results obtained are influenced by variations in the generalized procedure; namely, in the choice of disinfectant (259), the strength of the disinfecting solution, the immersion time in the solution, and the type of agar medium.

Fig. 1. Two lots of surface-disinfected oats plated on an agar medium and showing internally borne molds growing out from the lot on the left but not from the lot on the right. (Courtesy of C. M. Nagel.)

Late in the nineteenth century microorganisms were looked on as living forms of enzymes (22, 23, 24, 431, 432), which, always present within grains (34, 46, 128, 191, 192, 254, 255), were the source of diastase essential to seed germination (34, 46, 191, 192, 254, 255) and the cause of the normal decline of seed viability (164). When they were later recognized as distinct forms of living things differing from the inanimate enzymes found in grain, it was generally believed that they were absent from the interior of most grains (63, 215, 230, 233). This view persisted (35, 313) until recent observations revealed an almost universal occurrence of fungus mycelium in the pericarp of grains (77, 177, 178, 293). A typical photograph of mold mycelium on the inner side of the pericarp of a normal wheat kernel is shown in Figure 2.

It is now known that the parasitic fungi and bacteria listed in Table I may be carried internally. Semiparasites and saprophytes, such as *Nigrospora oryzae, Cephalosporium acremonium, Microascus trigonosporus* (430), *Penicillium oxalicum,* Penicillium spp., Aspergillus spp., Rhizopus spp., Alternaria spp., and a miscellaneous group of other fungi and bacteria may also be carried within grains. Their presence in kernels

depends on their own parasitic aggressiveness, on the action of true parasites, on the stage of grain development when they are present in the air (7, 247, 346), on grain susceptibility (59, 247), and on weather (7, 118, 409).

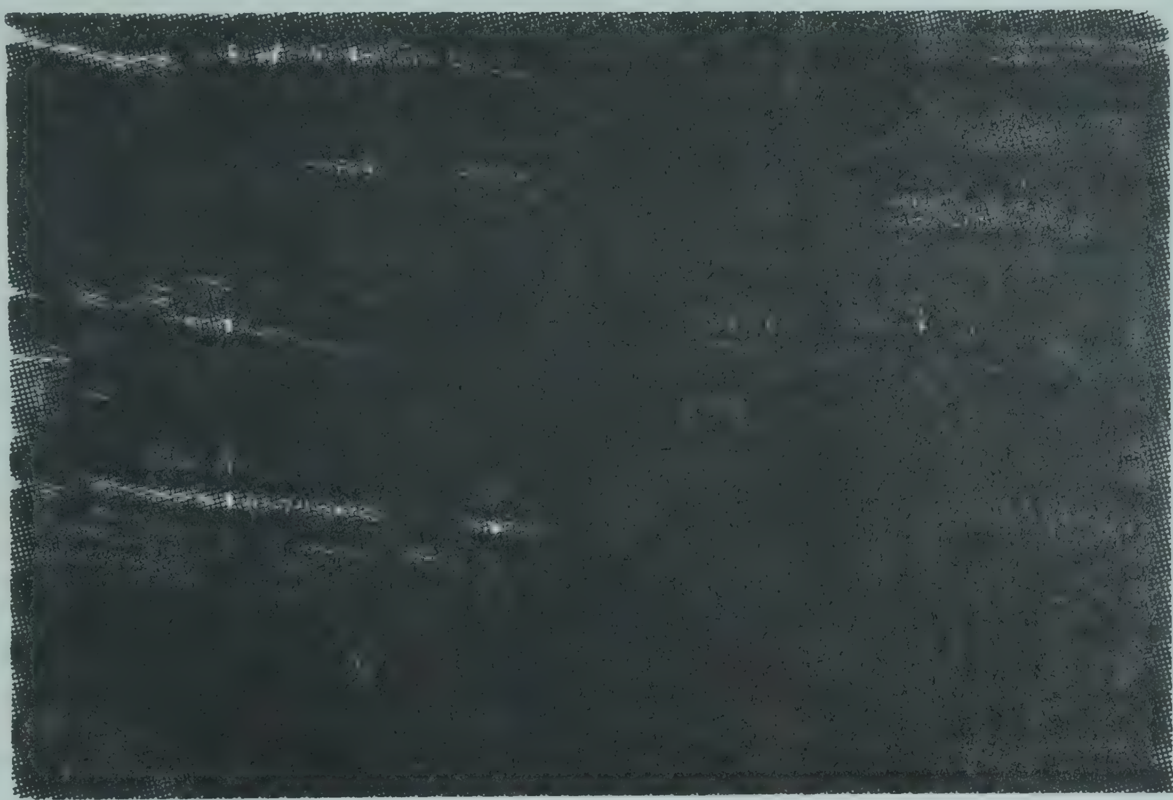

Fig. 2. Mold mycelium on the inner side of the pericarp of a normal wheat kernel. (Courtesy of C. M. Christensen.)

With some parasites, such as *Diplodia zeae, Helminthosporium sativum,* and *Gibberella zeae,* early infection produces shrivelled, blemished kernels, while late infection has no effect on the appearance of the kernels. With other fungi, such as *Ustilago nuda, U. tritici, Helminthosporium gramineum,* and *Microascus trigonosporus,* infection occurs early and there is no outward evidence of their presence. Hyphae of parasites may occur in the pericarp (187, 235, 253, 261, 288, 314, 371, 429), aleurone layer (185, 187, 288, 314, 429), endosperm (314, 429), or embryo (187, 253, 314, 353, 429). Penetration of hyphae into the deeper parts of kernels is resisted by a membrane, located between the nucellus and the inner integument. This membrane becomes thicker as the grains mature, though the thickening is less over the embryo (187, 261, 314, 394).

In Manitoba, Canada, over the years 1937 through 1942 (140), Alternaria species were present in approximately 70% of the kernels of wheat, oats, barley, and rye; Helminthosporium spp. were present in approximately 4%, and Fusarium spp. in approximately 1.5% of the kernels. Fungi of the genera Nigrospora, Curvularia, Epicoccum, Cephalothecium, Septoria, Pullularia, Cladosporium, Stemphylium, Penicillium, Aspergillus, and Mucor, in order of decreasing abundance, were

TABLE I

PARASITIC FUNGI AND BACTERIA CARRIED INTERNALLY BY CEREAL GRAIN SEEDS
(Adapted from Dickson, 96, Greaney and Machacek, 140)

Parasites	Wheat	Oats	Barley	Rye	Corn
Fungi					
Calonectria graminicola	+			+	
Colletotrichum graminicolum		+		+	
Diplodia macrospora					+
D. zeae					+
Fusarium spp.	+	+	+	+	+
Gibberella fujikuroi					+
G. zeae	+	+	+	+	+
Helminthosporium carbonum					+
H. gramineum			+		
H. sativum	+	+	+	+	
H. victoriae		+			
Pyrenophora avenae		+			
P. teres			+		
Septoria avenae		+			
S. nodorum	+				
S. secalis				+	
S. tritici	+				
Ustilago avenae		+			
U. nuda			+		
Bacteria					
Bacterium stewartii					+
Pseudomonas coronafaciens		+			
Ps. striafaciens		+			
Xanthomonas translucens	+		+	+	

present in approximately 6% of the kernels. Bacteria, yeasts, and actinomycetes were less prevalent. Over these same years, an average of 23.9% of wheat kernels, 25.2% of oat kernels, 13.6% of barley kernels, and 20.8% of rye kernels were internally free of microorganisms. During 1939 (139), bacteria and species of Alternaria, Helminthosporium, and Fusarium were more prevalent in cereal grains from Eastern Canada than from Western Canada where the climate is drier. Fifty genera of fungi and bacteria were found in grains grown in Canada that year. The lowest percentages of infected kernels were in wheat (8%) and oats (13%) from Alberta and in rye (27%) from British Columbia.

In the north-central part of the United States, species of Alternaria, Helminthosporium, Fusarium, and Gibberella are common in wheat, barley, and oats but are rarely found in grain produced in the semiarid sections of western South Dakota, western North Dakota, and Montana (390, 392, 393). Their abundance in the north-central region varies between locations and years according to the weather (45, 59, 81, 95, 97, 116, 189, 390, 391, 392, 393). Other microorganisms that are prevalent in grains grown in the United States are species of Aspergillus, Penicillium,

Acremoniella, Nigrospora, Cephalothecium, Hormodendrum, Phoma, Trichoderma, Rhizopus, and bacteria. Similar kinds of microorganisms have been observed in grains produced in other countries (91, 100, 109, 112, 119, 315, 378, 441).

In corn, 25% of the railroad cars that arrived at various terminals in the United States from 1916 through 1933 carried more than 5% damaged kernels (373). A larger percentage of cars with more than 5% damaged kernels arrived from Iowa, Illinois, Indiana, and Ohio over these years than from Colorado, Kansas, Nebraska, Texas, Kentucky, and Missouri. *Fusarium moniliforme, Diplodia zeae, Gibberella zeae,* and *Nigrospora oryzae* were probably the predominant fungi in such kernels.

Over the years 1933 through 1942 in the United States (172) *Diplodia zeae* and *Gibberella zeae* were more prevalent in damaged corn kernels from states east of the Mississippi River than from states west of the river. *Fusarium moniliforme* was more prevalent west of the river in the northern part of the country, and also in the southern states of Kentucky, Tennessee, Alabama, and Mississippi where corn earworms are abundant, than in other sections of the country. *Nigrospora oryzae,* infrequently found in normal years, was unusually abundant in 1935, as it was in Minnesota, Iowa, North Dakota, South Dakota, and Nebraska in 1942 when there was an early frost. Mucor and Aspergillus species were generally more abundant in South Dakota, Nebraska, Kansas, and Texas than in other parts of the country, while Penicillium species were relatively more abundant in the east-central and west-central sections. Over the four years 1932-35, Fusarium spp. were most common, and representatives of the genera Penicillium, Rhizopus, Diplodia, Gibberella, Nigrospora, and Aspergillus were least common, in the rotted kernels present in 28 to 90% of the corn ears produced in Illinois (43). During one year, *Fusarium moniliforme* was present on every ear of corn examined from many midwestern states, and it was present in every kernel of 60 representative ears examined (412). Also during one year, *F. moniliforme, Diplodia zeae,* or *Cephalosporium acremonium* was found in most of the kernels of nearly every ear examined in Missouri (55).

External Microflora

Saprophytes are the main components of the external microflora. They are present on grain from all areas since they are constantly in the air and in dust particles. Parasites may also be present. The external microflora thus includes (a) parasites that are partly on the surface and partly within the tissues of grain, (b) saprophytes that have adhered to the seed or have lodged between the hulls and caryopsis, (c) saprophytes that have developed on the surface of grain as epiphytes, and

(d) saprophytes and parasites that are loosely associated with grain but have not developed thereon (e.g., ergot sclerotia, smut spores, spores or mycelia of other fungi carried by plant debris and dirt). Some constituents of the external microflora may be detected by visual inspection of the grain, others by a microscopic examination of aqueous washings, and still others by culturing the washings in a gelatin or agar medium. Many microorganisms are so firmly embedded in the surface of grain that they resist removal by repeated washing with water and sand (102, 183, 419), but are readily removed with a detergent (77).

Molds. As on plant foliage (31, 102), fungi generally are present on cereal grains, having been reported in the following numbers:

0 to 44,000 per 0.1 g. of Russian or German wheat, oats, barley, and rye tested on a beerwort agar medium (167)

98 to 920 per g. of wheat from various countries and tested on a boullion agar or a boullion gelatin medium (367)

420 to 1,870 per g. of red spring wheat passing through trade channels at Winnipeg, Canada, during certain 2-week periods of the summers of 1943 and 1945, and tested on a Czapek agar medium (183)

3,330 to 8,500 per kernel of wheat from eight commercial samples in the United States and 20,000 to 56,665 per kernel of wheat from three commercial samples in the same country, as revealed by counting spores in the wash-water (69)

Mold counts have appeared to be the same on wheat grading No. 1 to No. 6 (183), on vitreous, immature, and frosted wheat kernels (183), and on wheat in the milk, dough, and mature stages of development (320). On the other hand, smaller numbers have been reported for high-grade than for low-grade wheat (77).

Morgenthaler (278) found 1,200 to 41,600,000 mold colonies per g. of musty grain and no colonies from sound grain when he ground common wheat, spelt, and rye in water and added the supernatant liquids to a gelatin or agar medium. However, he obtained 4,000 to 7,200 mold colonies per g. of normal wheat, 10,000 and 15,000 colonies per g. of slightly smutty wheat, and 184,000 colonies per g. of markedly smutty wheat when he added the supernatant liquids to a honey-gelatin medium. Christensen and Gordon (79) ground wheat and corn to a meal and added the meal to a malt-salt agar medium. They obtained 2,010 to 3,460 mold colonies from 1 g. of sound wheat, 5,000 molds from an immature wheat, and 66,000 molds from a "sick" wheat. Corn of the 1946 crop, obtained from five midwest terminals, yielded progressively larger numbers of molds as the corn grade number increased from 1 to 5, and to sample grade.

The molds that have been found on grain surfaces are as follows:

Penicillium and Colletotrichum species as most abundant, and Aspergillus, Alternaria, Cephalothecium, and Helminthosporium species as least abundant on wheat in North Dakota (44).

Spores of *Gibberella zeae*, smut fungi, *Colletotrichum cereale*, and *Cephalothecium roseum* on most wheat and oat samples from Ohio (347).

Spores of the genera Helminthosporium, Fusarium, Alternaria, Heterosporium, and of smut fungi and fragments of light and dark mycelium, on 15 barley varieties from Saskatchewan (260).

Alternaria, Helminthosporium, Fusarium, Epicoccum, Cladosporium, Penicillium, Aspergillus, and Mucor species, in order of decreasing abundance, on wheat, oats, and barley from Manitoba (140).

Cladosporium herbarum, Dematium spp., *Aspergillus versicolor*, *Penicillium lanosum* on wheat in the U.S.S.R. (320).

James, Wilson, and Stark (183) found the following on wheat:

Acrostalagmus cinnabarinus
Alternaria tenuis
Aspergillus glaucus
Aspergillus candidus
A. flavus
A. fumigatus
A. niger
A. oryzae
A. versicolor
Cephalosporium spp.
C. curtipes
Cephalothecium roseum
Fusarium culmorum
F. poae
F. scirpi var. *acuminatum*
F. semitectum var. *major*
Helminthosporium sativum
Hormodendrum pallidum
H. viride
Mucor circinelloides
M. racemosus
Paecilomyces varioti
Penicillium chrysogenum
P. flavi-dorsum
P. frequentans
P. purpurogenum
P. rugulosum
P. spinulosum
P. terrestre
Rhizopus spp.
Scopulariopsis spp.
S. brevicaule
Septoria nodorum
Trichoderma lignorum

On low- and high-grade wheat Christensen (77) found Aspergillus glaucus predominant over other fungi; the other fungi on high-grade wheat being *Aspergillus candidus* and species of Penicillium, Alternaria, Helminthosporium, and Fusarium, and on low-grade wheat *Aspergillus versicolor, A. niger, A. flavus, A. ochraceus,* and Penicillium spp.

Aspergillus glaucus, *Cladosporium herbarum*, and species of Aspergillus, Penicillium, and Alternaria have been obtained from lodicules in normal barley (82) and in sterile florets of a two-rowed barley (242). *Helminthosporium sativum* also was obtained (260).

Yeasts and Yeastlike Fungi. Yeasts and yeastlike fungi have been observed on grains (69, 140, 183, 320) but they have not been thoroughly investigated. James, Wilson, and Stark (183) reported 6,400 to 64,000 yeast colonies from 1 g. of wheat and progressively greater numbers on wheat grading from No. 1 to No. 6. The numbers were not significantly different on vitreous, weathered, immature, and frosted kernels. *Monilia* sp. and *Torula* sp. were the yeastlike fungi identified.

Other yeastlike fungi that have been reported from grain include:

Candida albicans (79)
C. humicola (98)
C. krusei (250)
C. pseudotropicalis (52)
Oospora sp. (320)
O. abortifaciens (332)
O. aegeritoides (406)
O. variabilis (32)
O. verticillioides (239, 406)
Chromosporium maydis (332)
Fusidium griseum (350)
Geotrichum candidum (syn. *Oospora lactis*) (239)
Monilia sitophila (332)
Trichosporium maydis (239)
Species of Rhinotrichum (350)
Species of Sporotrichum (364)
Species of Torula (110)
Species of Torulopsis (320)

Chrzaszcz (82) and Lindner (242) obtained *Dematium pullulans, Sphaerulina Tulasnei, Saccharomyces ellipsoideus, S. pastorianus, S. anomalus, S. apiculatus,* and species of Mycoderma, Torula, and Oidium from barley lodicules.

The fermentation industries (133, 158, 242, 339) report fermenting and nonfermenting types of "wild" yeasts on germinating barley, malt, wort, and in commercially prepared yeast; the fermenting types include, *Saccharomyces cerevisiae* var. *ellipsoideus* and *S. pastorianus,* while the nonfermenting types include:

Hansenula (Willia) anomala
Pullularia (Dematium) pullulans
Mycoderma cerevisiae
Cryptococcus (Torula) sanguinea
C. utilis
C. pulcherrima
Candida vulgaris (Monilia candida)
Trichosporon variable (Monilia variabilis)
Geotrichum candidum (Oidium lactis)
Pichia sp.

Bacteria. Bacteria outnumber the molds on grain and are present in nearly all bulk quantities of grain and on most kernels (183, 232, 367). They are present on wheat at various stages of development (321). Their abundance, as reported by different investigators, is shown in Table II.

TABLE II

NUMBERS OF BACTERIA REPORTED ON THE SURFACE OF CEREAL GRAINS

Investigator	Quantity of Kernels	Barley	Wheat	Oats	Rye
Hoffmann (167) 1896	0.1 g.	64,000–774,000	9,000–240,000	112,000–1,164,000	19,000–282,000
Becker (25) 1897	1.0 g.	5,000–12,000,000	....	....	....
Behrens (26) 1897	1.0 g.	Up to 10,000,000	14,000–23,000 256,000–309,000	More than 4,000,000	Up to 1,000,000
Düggeli (102) 1904	One kernel	3,100–80,000	83–43,000	1,700–35,000	23–3,000
Morgenthaler (278) 1918	1.0 g.	....	80,000–17,760,000 Average of 185,000	....	Average of 45,920,000
Woller (440) 1929	One kernel	12,000–24,000	18,000–56,000	4,600–23,000	9,600–280,000
Kent-Jones and Amos (200) 1930	1.0 g.	....	8,000–8,000,000	....	....
Gustafson and Parfitt (144) 1933	1.0 g.	....	46,000–3,260,000	....	....
Mack (249) 1936	One kernel	50,000	60,000	200,000	200,000
Soenen and Pinguair (367) 1937	1.0 g.	8,080–643,930	....	....	....
Rautenstein (320) 1939	1.0 g.	....	570,000–70,900,000	....	....
James, Wilson, and Stark (183) 1946	1.0 g.	....	280,000–164,000,000	....	....

Greater numbers of bacteria have been found on wheat when its wash-water was cultured at 20°C. than at 37°C. (200). Progressively greater numbers have been reported on Canadian wheat of grades No. 1 to No. 6 and on vitreous, weathered, immature, and frosted kernels, in that order (183). However, there is no assurance that a high-quality grain will carry a low bacterial count (183, 367). Fewer numbers have been found on musty rye and musty spelt than on corresponding normal grain, but the reverse has been noted with common wheat (278).

The bacteria on grain surfaces, exclusive of the phytopathogens listed

TABLE III

BACTERIA FOUND IN GRAINS, GRAIN MEALS, GRAIN MASHES OR MALT
(Synonymy of Breed *et al.*, 58)

Pseudomonadaceae

Pseudomonas maidis (Eisenberg) Migula (58)
[a]*Pseudomonas trifolii* Huss (syn. *Bacterium herbicola aureum* Burri and Düggeli, 102, 131, 183, 217, 222, 274, 275, 278, 320, 438, 440)
[a]*Pseudomonas fluorescens* Migula (syn. *Bacterium fluorescens* (Flügge) L. and N., 102, 222, 278)
[a]*Pseudomonas putida* (Trevisan) Migula (syn. *Bacterium putidum* (Flügge) L. and N., 102)
[a]*Pseudomonas punctata* (Zimmerman) Chester (syn. *Bacterium punctatum* L. and N.)
[a]*Acetobacter rancens* Beijerinck (30)
[a]*Acetobacter oxydans* (Henneberg) Bergey *et al.* (syn. *Bacterium oxydans* Henneberg, 154)
[a]*Acetobacter industrium* (Henneberg) Bergey *et al.* (syn. *Bacterium industrium* Henneberg, 154)

Micrococcaceae

Micrococcus pulcher Weiss (427)
[a]*Micrococcus pyogenes* var. *albus* (32)
Micrococcus zeae Serbinow (58)
Micrococcus ureae-liquefaciens Flügge (5)
Pediococcus acidi lactici Lindner (155, 157, 242)
Pediococcus lindneri Henneberg (157)
[a]*Sarcina maxima* Lindner (241, 242)

Lactobacteriaceae

Lactobacillus betadelbrueckii Kitahara (58)
Lactobacillus caneus Kitahara (58)
Lactobacillus leichmannii Fred, Peterson, and Stiles (124, 174)
Lactobacillus xylosus Kitahara (58)
[a]*Lactobacillus buchneri* (Henneberg) Bergey *et al.* (syn. *Bacillus wehmeri* Henneberg, 157)
[a]*Lactobacillus delbrueckii* (Leichmann) Beijerinck (syns. *Bacillus acidificans longissimus* Lafar, 223; *Bacillus delbrueckii* Leichmann, 155; *Thermobacterium cereale* Orla-Jensen)
[a]*Lactobacillus plantarum* (Orla-Jensen) Holland (174) (syns. *Bacillus maercki* Henneberg, 156, 157; *Streptobacterium plantarum* Orla-Jensen)
[a]*Streptococcus lactis* (Lister) Löhnis (syns. *Bacillus lactis acidi* Leichmann, 234: *Bacterium leichmanni* Wolff. 437; *Bacterium güntheri* L. and N., 222; *Streptococcus acidi lactici* Grotenfeldt)

[a] Species recognized by Breed et al. (58)

TABLE III (Continued)

BACTERIA FOUND IN GRAINS, GRAIN MEALS, GRAIN MASHES OR MALT
(Synonymy of Breed *et al.*, 58)

Achromobacteriaceae

Flavobacterium sp. (5)
Achromobacterium sp. (5)

Enterobacteriaceae

[a] *Aerobacter aerogenes* (Kruse) Beijerinck (syns. *Bacterium acidi lactici* Hueppe, 113, 433; *Bacterium lactis aerogenes* Escherich, 433)
[a] *Aerobacter cloacae* (Jordon) Bergey *et al.* (syn. *Bacillus levans* Lehmann and Wolffin, 439)
[a] *Escherichia coli* (Migula) Castellani and Chalmers (syn. *Bacterium coli communis* Escherich)
[a] *Paracolobactrum aeroginoides* Borman, Stuart and Wheeler (49)
[a] *Paracolobactrum coliforme* Borman, Stuart and Wheeler (49)
[a] *Paracolobactrum intermedium* Borman, Stuart and Wheeler (49)
[a] *Proteus mirabilis* Hauser (58)
[a] *Proteus vulgaris* Hauser (58)
[a] *Serratia marcescens* Bizio (syn. *Bacillus prodigiosus* Flügge, 312, 441)

Bacteriaceae

Bacterium crenatum Weiss (427)
Bacterium esterificans fluorescens Maassen (246)
Bacterium gibbosum Weiss (427)
Bacterium gracilescens Weiss (427)
Bacterium herbicola a aureum Geilinger (131)
Bacterium herbicola rubrum Düggeli (102)
[a] *Bacterium linens* Weigmann (2)
Bacillus maydis Maiocchi (58)
Bacillus panificans Laurent (231)
Bacterium termo (Mueller) Ehrenberg (133, 242)
Bacterium uniforme Weiss (427)
[a] *Bacterium zopfii* Kurth

[a] Species recognized by Breed et al. (58)

TABLE III (Continued)

BACTERIA FOUND IN GRAINS, GRAIN MEALS, GRAIN MASHES OR MALT
(Synonymy of Breed *et al.*, 58)

Bacillaceae

Bacterium aqueum Migula (syn. *Bacillus thermophilus* VIII Rabinowitsch, 317)
[a] *Bacillus cereus* Frankland and Frankland (syn. or var. *Bacillus mycoides* Flügge, 275, 278)
Bacillus cylindricus Blau (syn. *Bacillus calidus* Blau, 311)
Bacillus flavescens Weiss (427)
Bacterium insulum Weiss (427)
Bacterium intactum Migula (syn. *Bacillus thermophilus* V Rabinowitsch, 317)
Bacterium lydiae Migula (syn. *Bacillus thermophilus* I Rabinowitsch, 317)
Bacillus maidis Paltauf and Heider (58)
[a] *Bacillus megaterium* De Bary (157)
[a] *Bacillus michaelisii* Prickett (syn. *Bacillus nondiastaticus* Bergey *et al.* 311)
[a] *Bacillus polymyxa* (Prazmowski) Migula (28, 29, 157, 308) (syn. *Bacillus asterosporus* Migula)
Bacillus pseudoanthracis Kruse (58)
Bacterium streptococciforme Migula (syn. *Bacillus thermophilus* III Rabinowitsch, 317)
[a] *Bacillus subtilis* Cohn emend. Prazmowski (157) (syns. *Bacillus vulgatus* (Flügge) Migula; *Bacillus mesentericus* (Flügge) L. and N., 123)
[a] *Bacillus viridulans* (Migula) Bergey *et al.* (syn. *Bacillus thermophilus* II Rabinowitsch, 317)
[a] *Clostridium acetobutylicum* McCoy *et al.* (58) (syn. *Butylobacter zeae* Bakonyi)
[a] *Clostridium butyricum* Prazmowski (syns. *Granulobacter butylicum* Beijerinck. 28, 29, 157; *Granulobacter saccharobutyricum* Beijerinck. 28, 29, 157; *Bacillus amylobacter* A. M. et Bredemann, 57)
[a] *Clostridium lentoputrescens* Hartsell and Rettger (58) (syn. *Bacillus putrificus* (coli) L. and N., 222)
[a] *Clostridium roseum* McCoy and McClung (58)
[a] *Clostridium viscifaciens* Sherman and Erb (58)
Clostridium welchii (115)
[a] *Clostridium perfringens* (Veillon and Zuber) Holland (syn. *Granulobacillus saccharobutyricum immobilis liquefaciens* Shattenfroh and Grassberger, 58)

[a] Species recognized by Breed et al. (58).

in Table I, are saprophytes and include spore-formers and nonspore-formers, psychrophiles, mesophiles, and thermophiles; aerobes and anaerobes. They include representatives from the lactic acid bacteria, butyric acid bacteria, acetic acid bacteria, hay and potato bacilli, coliaerogenes bacteria, and others without common designation. Many bacteria have been detected on usual or special laboratory culture media by plating the wash-water obtained from the grains, while others have been detected in fermenting whole grains, grain meals, grain mashes, and malt. A list of them is presented in Table III.

Following Burri's study (67) of the bacteria prevalent on plant surfaces, Düggeli (102) found the epiphytic bacterial flora of cereal grains to be essentially the same as that of green foliage, while Wallace and Lochhead (419) found it to be different from the predominant bacteria in soil. The work of Burri and Düggeli showed *Bacterium herbicola aureum* to be most abundant, representing 86 to 100% of the bacteria on normal wheat, oats, barley, or rye kernels. *Bacterium fluorescens* (Flügge) L. and N. was next in abundance, followed by *Bacterium putidum* (Flügge) L. and N., *Bacterium megaterium* De Bary, *Bacillus vulgatus* (Flügge) Migula, *Bacillus mesentericus* (Flügge) L. and N., *Bacterium coli* (Escherich) L. and N., Streptothrix spp., and others that were not identified. Morgenthaler (278) found a similar abundance of *Bacterium herbicola aureum* on normal common wheat, rye, and spelt, the remainder of the bacterial population consisting of various combinations of cocci, *Bacillus prodigiosus, Pseudomonas fluorescens, Bacillus mesentericus, Bacillus mycoides,* coli, clostridia, and proteuslike bacteria. On most musty and sour samples of these same grains cocci formed the dominant bacterial flora, but in some samples it consisted of yellow Sarcina, proteuslike bacteria, or white colonies of rod-shaped bacteria.

Woller (440) found *Bacterium herbicola aureum* comprised 90 to 100% of the colonies from wheat and 95 to 100% of the colonies from rye. The spore-forming *Bacillus megaterium, B. mycoides, B. subtilis,* and *B. mesentericus* formed 80 to 90% of the population on barley and 70% on oats, with *Bacterium herbicola aureum* making up the remainder. However, *B. herbicola aureum* formed the entire bacterial population on dehulled barley and oats. James, Wilson, and Stark (183) reported *B. herbicola aureum* and a yellow-pigmented, fluorescent, pseudomonas-type bacterium as the dominant forms on wheat grains examined by them in Canada. Rautenstein (320, 321) found *B. herbicola aureum* dominant on wheat in the U.S.S.R.; it was frequently accompanied by small numbers of micrococci and sarcinae. Mishoustin (275) found only a single temperature strain of the dominant *B. herbicola aureum* on cereal grains produced at different latitudes in the U.S.S.R. and several

temperature strains of the subdominant *Bacillus mycoides*. Wallace and Lochhead (419) noted the predominant bacteria on wheat and oats to be nonsporing, nonpleomorphic, gram-negative rods, which were motile and chromogenic and able to ferment sugars and liquefy gelatin. Chrzaszcz (82) and Lindner (242) had reported *Bacillus mesentericus aureus* Winkler, Sarcina, pediococci, rod and cocci bacteria in the lodicules of barley.

The dominant bacterium on plant surfaces to which the descriptive name, *Bacterium herbicola aureum*, was applied by Burri (67) and Düggeli (102) was considered by these investigators to be identical with *B. mesentericus aureus* Winkler (434). Beijerinck and Rant (31) subsequently stated that *B. herbicola aureum* was the same as *B. anglomerans* Beijerinck. Mack (249) found *Pseudomonas trifolii* Huss (176) to be identical with a variety of *Bacterium herbicola aureum*, and suggested these be named *Flavobacterium herbicola*. Thaysen and Galloway (396) along with Beijerinck and Rant (31) and Kürsteiner (222) doubted the dominant position ascribed to *B. herbicola aureum* on plant surfaces, for the reason that other bacteria also produced yellow, transparent colonies on agar media. Mack (249), however, has since demonstrated that this bacterium is distinct from other yellow-pigmented bacteria and thus there now appears to be no reason to doubt the dominance of *B. herbicola aureum*.

Other bacteria that have been found to be prevalent on grains include *Bacterium linens* Weigmann (2), Clostridium spp. (29), *Acetobacter rancens* Beijerinck (30), *Micrococcus ureaeliquefaciens* Flügge (5), *Escherichia coli* (71, 265, 310, 326, 330, 361), and several lactobacilli (124, 174, 395). Henneberg (158) records the following bacteria in spontaneously fermenting mashes made of grain, of malt, and of bran: (a) Lactic acid bacteria, including "culture" lactic acid bacteria *(Lactobacillus delbrueckii, L. lactis, L. plantarum)*, "wild" lactic acid bacteria *(L. buchneri, L. brevis, Streptococcus lactis)*, pediococci, and *Sarcina maxima;* (b) acetic acid bacteria *(Acetobacter xylinum, A. rancens, A. industrium)*; (c) butyric acid bacteria (Clostridium spp.); (d) *Bacillus subtilis;* (e) *Bacillus megaterium;* and (f) putrefactive bacteria.

Actinomycetes. Actinomycetes are frequently detected in cereal grains (13, 33, 69, 140, 217, 320, 321), but little is known about their distribution. Morgenthaler (278) found them in 14 of 23 samples of wheat, in five of six samples of rye, and in each of four samples of spelt. Their numbers varied from 8,000 to 24,000,000 per g. of wheat, 40,000 to 9,280,000 per g. of rye, and from 19 million to 300 million per g. of spelt. The large numbers led Morgenthaler to suggest that the actinomycetes had increased during grain storage, but he considered them to be carried by

the soil particles mixed with the grain, rather than by the grain surfaces themselves. The following actinomycetes, which are streptomycetes, have been reported from cereal grains:

Streptomyces albus (Rossi-Doria em. Krainsky) Waksman and Henrici (321) (syns. *Actinomyces dassonvillei* Brocq-Rosseau, 60, 303; *Actinomyces graminearum* Berestnew, 33)
Actinomyces albido fuscus (33)
Actinomyces cinereus niger aromaticus (33)
Actinomyces globisporus (320)
Actinomyces graminis (51)
Actinomyces griseus (320)
Actinomyces violaceus (33, 321)

Microflora of Cereal Products

Fungi and bacteria in grain products are derived from the surface and interior of the parent grain, from the air, and from foreign materials, such as dirt and dust, that enter the products as contaminants. Microorganisms are most prevalent on and just beneath grain surfaces, and therefore cereal products containing these parts may be expected to carry a more varied and abundant microflora than those products that are derived largely from the endosperm.

Flour

Microorganism content of flour has been evaluated by methods involving three steps: (a) the flour is dispersed by shaking a weighed quantity in sterile water or physiological saline solution, with or without sand, (b) the resulting suspension is diluted to disperse individual microorganisms, and (c) the diluted suspension is added to gelatin or agar media, or to nutrient broth. The numbers of microorganisms found by this procedure are affected by such variables as the type of dispersion medium, period for dispersion, type of culture medium, pH of culture medium, and the temperature of incubation (76, 200). Another method, which has value for mold counts, is the application of dry flour to surfaces of semisolid nutrient media (76, 78).

Molds. Molds are found in nearly all flour samples, the following numbers per g. of flour having been reported:

1,400 to 58,000 colonies from wheat, rye, and mixed wheat and rye flours produced by 13 Swiss mills (131)
100 to 640 colonies from a soft-wheat flour having a wide distribution in the United States (170)
152 to 19,982 colonies on agar media and 0 to 11,640 on gelatin media from grade 00 wheat flour produced by 20 Belgian mills (367)
Averages of 1,000 to 2,000 colonies from flour milled in England (18)
Averages of 1,150 to 2,850 colonies on a Czapek's agar medium,

and 1,270 to 3,960 colonies on a malt-salt agar medium, from five brands of flour produced over a 10-week period by one Canadian mill (182)

225 to 5,180 colonies on a malt-salt agar medium from 20 samples of patent flour, one of cake flour, one of sponge flour, and three of clear flour obtained from mills in 13 of the United States (78)

The less pericarp a flour contains the lower is the mold count likely to be (170, 367). In one mill fewer molds were found in the first middlings flour stream over a 24-hour period than in the first break or first tailings flour streams (78). In another mill, the mold content was nearly alike in the first, second, and sixth middlings flours, and higher in the first, second, and fourth break flours and the first and second tailings flours. A reduction in mold content occurred between the first and fourth break flour streams in two mills, while an increase occurred in another mill.

Soenen and Pinguair (367) found no relationship between the mold population of grain surfaces and the mold content of flour. Twelve samples of wheat derived from different countries carried 98 to 920 molds per g. (average, 393), but the flours produced from them carried 0 to 4,223 molds per g. (average, 663). Half the flours carried a higher mold population than the original wheats. Furthermore, the proportion of molds to bacteria was larger for the flours than it was for the 12 wheat samples, suggesting that molds were entering the flour from an external source. Christensen and Cohen (78) found 5,000 to 2,456,000 molds per g. in accumulations of flour lodged in mill machinery and suggested that these accumulations were important sources of molds in flour.

The kinds of molds that are present in flour have been determined in only a few instances. Christensen and Cohen (78) found 75% Aspergillus glaucus, 15% *A. candidus*, and 10% Penicillium spp. in a bakers' patent flour, and principally *Aspergillus candidus* in a fourth break flour. They found Aspergillus glaucus and *A. candidus* predominating in most samples taken from flour lodged in the mill machinery, though sometimes *A. flavus* and Penicillium spp. were most abundant. The following were also present in small numbers in most of the samples:

Aspergillus ochraceus	*A. versicolor*
A. niger	*A. terreus*
Rhizopus nigricans	*Alternaria tenuis*
Mucor racemosus	Helminthosporium spp.
Hormodendrum spp.	Fusarium spp.

Strieder and McClellan (377) found *Rhizopus nigricans,* Aspergillus glaucus, *A. ostianus*, *A. candidus*, and Penicillium glaucum on flour lodged in bakeries. Barton-Wright (18) noted that Pencillium spp. com-

prised 90% of the molds present in a musty flour and were represented by *P. brevicompactum, P. patris-mei, P. expansum, P. cyclopium* (probably), and members of the monoverticillata-ramigena and fasciculata-viridicata groups of Thom (398). Species of Botrytis, Aspergillus, and Cladosporium were also present. Aspergillus glaucus and *Rhizopus nigricans* (410, 442) and *Aspergillus fumigatus* (334) have also been found in flour.

Yeasts and Yeastlike Fungi. Yeasts and yeastlike fungi in flour have not been investigated extensively. Holliger (168) occasionally noted small numbers of yeasts in flour, while Barton-Wright (18) has also observed their presence. James and Smith (182) reported averages of 54, 268, 12, 47, and 81 yeast colonies per g. from five brands of Canadian flour produced by one mill over a 10-week period, but the yeasts were not identified. Amos (5) found a Torula prevalent in flour, while Henneberg (158) reported culture top yeast *(Saccharomyces cerevisiae)* and a small egg-shaped yeast in a fermenting flour-water suspension held at 27°C. Wolffin (439) and Holliger (168) were unable to detect yeast development in a spontaneously fermenting dough prepared from flour and water.

Bacteria. The bacteria usually outnumber molds and yeasts in flour, as they do on grain surfaces. Ratios of bacteria to molds ranging from 1:0.007 to 1:2.46 have been obtained for freshly milled flours, and a ratio of 1:11.33 for flour stored 1½ years (131). Flour produced by 20 Belgian mills showed ratios of 1:0.004 to 1:0.48 when tested on agar media, and ratios of 1:0 to 1:0.85 when tested on gelatin media (367).

Thomann (401), who was among the earliest (39, 369) to determine the number of bacteria in flour, reported 20,000 bacteria per 1 ml. of a wheat flour and 16,000 bacteria from a mixture of wheat and rye flour. Dietzel, according to Geilinger (131), found similar numbers but noted a fivefold increase in the bacterial count when the flour was agitated in water for 25 minutes instead of 5. Geilinger (131) failed to obtain this increase when he agitated flour in a physiological salt solution, but nevertheless recommended 15 to 30 minutes' agitation. With 1-minute agitation, counts of 5,000 to 92,000 bacteria per g. were obtained on testing wheat flours, rye flours, and a mixed wheat and rye flour produced by 11 Swiss mills, while 1,740,000 bacteria were found in a mixed wheat and rye flour produced by another mill.

In Belgium, Soenen and Pinguair (367) reported results that varied from 1,115 to 70,943 bacteria per g. of grade 00 flour prepared by 20 different mills, while in England, Kent-Jones and Amos (200) obtained bacterial counts ranging from 5,000 to 10,000 per g. of patent flour produced over several weeks by one mill and from 23,000 to 35,000 per g.

of a straight-run flour. In Canada, five brands of flour produced by one mill carried average numbers of bacteria ranging from 2,750 to 19,500 per g. (182).

In the United States, Turley (410) examined flours from 17 different sources and obtained unusually high numbers of bacteria. His results ranged from 710,000 to 5,200,000 per g. of flour. Other investigators in the same country have reported smaller numbers. Fred (122) found 18,000 to 60,000 bacteria per g. in flours from different sources; Holtman (170) obtained 3,100 to 7,500 bacteria per g. in a popular brand of soft-wheat flour; and Gustafson and Parfitt (144) obtained results ranging from 9,000 to 380,000 bacteria per g. for patent, straight, and clear flours milled from soft wheat at 20 different places.

Flour derived from the central part of the endosperm generally contains fewer bacteria than flour coming from near the bran or the embryo (144, 170, 200, 367). Soenen and Pinguair (367), however, failed to find a relationship between the surface bacterial population of wheat and the bacterial population of flour, although Kent-Jones and Amos (200) noted an increase in the bacterial content of flour after the wheat had been subjected to an abnormally long conditioning process involving the use of moisture. Mirzoieva (274) attributed high numbers of rope-producing bacteria in flour to the use of wheat that had been stored with a high moisture content. Screening, scouring, aspirating, and chemically disinfecting the grain before milling lowered the microbial population of grain surfaces (200, 367), but mill dust and flour lodged within the machinery acted as flour contaminants. Kürsteiner (222) examined 24 samples of mill dust, consisting of particles of soil, bran, plant hairs, and starch. The populations ranged from 1,280,000 and 305,000,000 bacteria per g. with an average of 62,700,000 per g. One sample of pure endosperm carried 51,000 bacteria per g.

The species of bacteria that have been isolated from flour and flour products are nearly the same species as those present on grain surfaces. They are listed in Table IV.

The following is a more detailed record of the bacteria that have been reported (a) in flours, (b) in spontaneously fermenting flour-water doughs, (c) in fermenting suspensions of flour in water, and (d) in mill dust.

(a) In flour: Bacillus α and Bacillus β (54); *B. panificans* (231); Sarcina spp. (142); *Granulobacillus immobilis* (335); *Bacillus mesentericus*, *B. fluorescens liquefaciens*, two diplococci, and several gelatin nonliquefying bacilli (401); *Bacterium herbicola aureum* (131); *Aerobacter aerogenes* and *Bacillus mesentericus* as predominant over species of Sarcina, Achromobacter, Flavobacterium, and an agar-digesting form related to

TABLE IV

BACTERIA FOUND IN FLOUR, FLOUR PASTE, AND BREAD DOUGH
(Synonymy of Breed *et al.*, 58)

Pseudomonadaceae	
	[a] *Pseudomonas fluorescens* (syns. *Bacillus fluorescens liquefaciens* Flügge, 401; *Bacterium fluorescens* L. and N., 168, 222)
	[a] *Pseudomonas putida* (Trevisan) Migula (syn. *Bacterium putidum* L. and N., 222)
	[a] *Pseudomonas trifolii* Husse (syn. *Bacterium herbicola aureum* Burri and Düggeli, 131, 274)
Micrococcaceae	
	Micrococcus ureae-liquefaciens Flügge (5)
	Micrococcus zeae Serbinow (58)
	Pediococci (158)
	[a] *Sarcina maxima* Lindner (241)
	Sarcina spp., unclassified (142, 170)
Lactobacteriaceae	
	Diplococcus spp. (401)
	[a] *Lactobacillus delbrueckii* (Leichmann) Beijerinck (syn. *Bacillus delbrueckii*, 158)
	Lactobacillus leichmannii (174)
	[a] *Lactobacillus plantarum* (Orla-Jensen) Holland (syn. *Streptobacterium plantarum*, 158, 174)
	[a] *Streptococcus lactis* (Lister) Lohnis (syns. *Bacterium güntheri* L. and N., 222; *Bacterium lactis acidi* Leichmann, 168)
	[a] *Streptococcus pyogenes* Rosenbach (310)
Achromobacteriaceae	
	Flavobacterium sp. (5, 170)
	Achromobacterium spp. (5, 170)

[a] Species recognized by Breed et al. (58)

TABLE IV (Continued)

BACTERIA FOUND IN FLOUR, FLOUR PASTE, AND BREAD DOUGH
(Synonymy of Breed *et al.*, 58)

Enterobacteriaceae
- [a]*Aerobacter aerogenes* (Kruse) Beijerinck (170)
- [a]*Aerobacter cloacae* (Jordan) Bergey *et al.* (syns. *Bacillus levans* Lehmann and Wolffin, 168, 297, 439; *Bacterium coli albidoliquefaciens* Lehmann and Levy, 238; Holliger's white gas-former, 168)
- [a]*Escherichia coli* (Migula) Castellani and Chalmers (syns. *Bacterium coli* L. and N., 222, 310; *Bacterium coli communis* Escherich, 5; probably *Bacterium acidi lactici* Hueppe, 222)
- Proteus spp. (*Bacterium coli luteoliquefaciens* Lehmann and Levy, 222, 238; Holliger's yellow gas-former 168)

Bacteriaceae
- *Bacillus panificans* Laurent (231)
- Bacillus α and β (54)

Bacillaceae
- [a]*Bacillus megaterium* De Bary (158, 168)
- [a]*Bacillus subtilis* Cohn emend. Prazmowski (5, 6, 19, 131, 138, 168, 200, 243, 274, 401)
- [a]*Clostridium butyricum* Prazmowski (syns. *Granulobacter butylicum* Beijerinck, 29; *Granulobacterium saccharobutyricum* Beijerinck, 29)
- [a]*Clostridium lentoputrescens* Hartsell and Rettger (*Bacillus putrificus* Bienstock, 222)

[a] Species recognized by Breed et al. (58)

Cellulomonas (170); lactic and acetic acid bacteria (89); *Bacterium coli communis, Bacillus perfringens,* strains of *Bacillus subtilis, Streptococcus lactis, Micrococcus ureae-liquefaciens,* and species of Flavobacterium and Achromobacterium (5); *Bacterium putidum* and *Bacillus putrificus* (222); a *B. mycoides*-like bacterium that did not liquefy gelatin (222); *Bacterium coli, Streptococcus pyogenes* (310): *Bacterium prodigiosum* (148), and many strains of *Bacillus subtilis* (6);

(b) In spontaneously fermenting flour-water dough; *Bacillus panificans* (231); *B. levans* (439); *B. megaterium, B. lactis acidi, B. levans, B. vulgatus, Bacterium fluorescens,* short-rod bacteria that form small yellow colonies and that liquefy gelatin, and anaerobic, butyric acid bacteria (168); *Bacillus levans* and five other bacteria, four of which form lactic acid (348); *Streptobacterium plantarum* and coli-like bacteria (157);

(c) In water suspension of wheat flour held at 27°C.: Pediococci, *Bacillus conglomeratus, B. megaterium, B. levans,* and *B. delbrueckii*-like bacteria (157);

(d) In mill dust: *Bacterium herbicola aureum, B. fluorescens* (Flügge) L. and N., Micrococci, *Bacterium güntheri* L. and N., *B. acidi lactici* Hueppe, *B. coli* (Escherich) L. and N., *Bacillus putrificus* Bienstock, *Bacterium coli luteoliquefaciens* Lehmann and Levy, *Sarcina* sp., and *Bacterium putidum,* from the most to the least prevalent (222).

Among flour samples from different sources Geilinger (131) noted variations in the proportion of bacteria producing yellow colonies on gelatin media and also noted that the proportion increased during dry storage. Soenen and Pinguair (367) observed three to five kinds of undescribed bacteria in flour and noted that gelatin-liquefying bacteria comprised 0 to 66% of the total bacterial population. These percentages were generally higher than were obtained in tests on the parent grain. James and Smith (182) found 39 to 1,760 acid-producing bacteria per g., 47 to 822 spore-forming bacteria, 22 to 176 "flat-sour" bacteria, 49 to 85 presumptive "rope"-producing bacteria, and 0 to 2 anaerobic, thermophilic bacteria. Other investigators, also, have noted variations among flours in the content of "rope"-producing bacteria (6, 19, 243, 274, 401) and thermophiles (446), and it has been reported that these bacteria are usually most abundant in flour containing bran (19, 446).

Bran

Molds. A variety of molds has been observed in the pericarp (14, 77, 177, 178, 293, 345) and bran (20, 34, 165). Gordan (135) obtained mold counts of several hundred thousand or more per g. of rye bran and of wheat bran when aqueous suspensions of these products were added to a meat-extract-peptone gelatin medium. Soenen and Pinguair

(367) reported 2,650 molds per g. of wheat bran on an agar medium, and 4,820 molds per g. on a gelatin medium; contamination of the bran during milling was suggested because it came from a wheat whose surface tested mold-free. Christensen and Cohen (78) found 750 to 3,000 molds per g. in four bran samples collected over a 24-hour period in one mill, and 1,200, 1,900, and 2,650 molds per g. in three samples derived from three mills. Their samples were finely ground and added directly to a malt-salt agar medium.

The following molds have been found: Aspergillus spp. and Penicillium spp. (78); *Aspergillus repens, A. ruber,* and *A. candidus* (364); 64% *Alternaria tenuis,* 7.7% *Mycogone* sp., 5.8% *Cladosporium herbarum,* 4.8% *Pullularia pullulans,* 1.9% *Fusarium* sp., 1.9% *Botrytis cinerea,* and 0.9% *Stemphylium botryosum* in the epidermis of wheat (178); mainly Aspergillus glaucus, *A. tamarii,* and *Alternaria* sp. in the pericarp of low-grade wheat, and mainly *Alternaria* sp. in the pericarp of high-grade wheat (77).

Bacteria. In bran, bacteria have been reported in these numbers: 400,000 to 23,700,000 per g. in 12 samples of rye bran and wheat bran (135); 2,000,000 per g. in one bran sample (114); approximately 700,000 per g. from a bran derived from a surface-cleaned wheat (367); and an average of 5,976,000 per g. for 15 bran samples, with an average of 4,709,000 per g. for eight finely ground samples, and of 7,424,000 per g. for seven coarsely ground samples (433).

Esten and Mason (114) noted 30% of the bacteria in bran examined by them produced acid, while 10% liquefied gelatin. Similarly, Soenen and Pinguair (367) found 16.5% of the bacteria in their bran sample liquefied gelatin. The species that have been found in bran are as follows: *Clostridium* sp (164); *Bacillus liquefaciens, B. flavus colisimilis,* and *Bacterium coli* (135); lactic acid bacteria (174); and 23 species (433) of which the most abundant were *Bacterium herbicola aureum,* Holliger's yellow gas-former, Levy's yellow acid-former, *B. fluorescens, Bacillus mesentericus,* and *B. acidi lactici,* and the least abundant, *B. tumescens, B. putrificus coli, B. coli commune, B. megaterium, B. mycoides, B. anthracis, Bacterium güntheri, B. lactis aerogenes, B. putidum, B. punctatum, B. vulgare,* a *B. levans*-like bacterium, a white Streptothrix, and unidentified species.

Grain Meals

Of the grain meals, only those prepared from corn appear to have been analyzed for their microbial content.

Molds. Hiltner (165) found 145,000 molds and Geilinger (131) 3,500 molds per g. of cornmeal. Thom and LeFevre (399) reported 3,000 to 400,000 molds per g. of commercially available cornmeal and 70,000 to

160,000 per g. of freshly prepared cornmeal. Bolted cornmeal proved lower in mold content than nonbolted.

The following fungi are reported to be common in cornmeal (399):

Cladosporium sp.	*P. purpurogenum*
Alternaria sp.	*Aspergillus repens*
Rhizopus nigricans	*A. fumigatus*
Mucor spp.	*A. flavus*
Syncephalastrum sp.	*A. niger*
Penicillium oxalicum	*A. tamarii*
P. luteum	Citromyces spp.
Yeasts of the Mycoderma type	

Bacteria. The following numbers of bacteria have been reported in grain meals: 74,000 (165), 3,200,000 (114), 180,000 (131), and 15,000 (181) per g. of cornmeal for individual samples; from 5,000 to 60,000 per g. in commercially available cornmeal, and from 600,000 to 1,600,000 per g. in freshly prepared cornmeal (399).

Bacteria forming yellow colonies on a gelatin medium comprised 44% of the total bacteria in the cornmeal examined by Geilinger (131). Acid-producing bacteria comprised 30 to 100% (average 57%) of the bacteria in the commercial cornmeal examined by Thom and LeFevre (399). In their samples *Bacterium aerogenes* and *Bacillus mesentericus* predominated over micrococci, lactobacilli, and *Bacillus niger.* James, Rettger, and Thom (181) found *B. subtilis, B. vulgatus,* and *Proteus vulgaris* in cornmeal; Geilinger (131) found *Bacterium herbicola α aureum;* Hunt and Rettger (174) found several lactobacilli; Esten and Mason (114) found *B. lactis acidi;* while Heinemann and Hefferan (150) found a lactic acid bacterium resembling *Bacillus bulgaricus.*

Principal Environmental Factors Influencing the Activity of Microflora

Microorganisms grow and sporulate when the factors of the environment are favorable, and perish or become dormant when these are unfavorable. Growth occurs over wider ranges of environmental conditions than sporulation (195, 206). Their dormant state, which is an intermediate phase between growth and death, may be of short or long duration, depending on the environment and on the innate properties of the dormant cells. The features of the environment which are of most importance in determining the activity of microorganisms in stored grain and grain products are temperature, moisture, and oxygen supply. The influence of each of these factors is considered in the following sections.

Temperature. Microorganisms differ in their thermal requirements for growth and commonly are classified as psychrophiles, mesophiles, and thermophiles. Their required temperatures for growth – minimum, optimum, and maximum, respectively – are: psychrophiles, –8° to 0°,

TABLE V

NEAR-MINIMUM GROWTH TEMPERATURES OF SOME PSYCHROPHILIC MICROORGANISMS
(Mainly after Chistiakov *et al.*, 73, 74)

Temperature	Bacteria	Fungi
°C.		
−8	*Flavobacterium sulfureum* *Bacterium lactis viscosum*	Aspergillus glaucus *Chaetostylum fresenii* *Thamnidium elegans* Oospora spp. A yeast
−5	*Bacterium fluorescens* *Flavobacterium lutescens* *F. ochraceum* *Flavobacterium* sp. *Micrococcus* sp.	*Fusarium culmorum* Fusarium spp. Penicillium spp. Cladosporium spp. *Botrytis cinerea* *Monilia nigra* *Torula rubefaciens* *Torula* sp. A pink torula Apiculatus yeast *Pichia* sp.
−4	......	*Penicillium chrysogenum*
−3	......	*Mucor racemosus* *Penicillium digitatum* *P. expansum* *P. glauco-griseum* *Penicillium luteum*
−2	*Bacterium putidum* *Achromobacter* sp.	*Phycomyces nitens* *Saccharomyces intermedius* *S. kefii* *S. turbidans*
0	*Bacterium carotovorum* *B. prodigiosum* *B. coli albidoliquefaciens* *Sarcina* sp.	*Penicillium palitans* *P. rugulosum*

10° to 20°, and 25° to 30°C.; mesophiles, 5° to 25°, 20° to 40°, and 40° to 45°C.; thermophiles, 25° to 40°, 50° to 60°, and 70° to 80°C.

Thermal requirements of representatives within each of these classes are given in Tables V, VI, and VII.

Microorganisms grow faster and sporulate sooner as the temperature approaches their optimum (73, 161, 206), and they usually sporulate within narrower ranges of temperature than those which permit their growth; sexual sporulation occurs within narrower temperature ranges than asexual sporulation (Table VIII). Their minimum and maximum

TABLE VI

CARDINAL GROWTH TEMPERATURES OF SOME MESOPHILIC MICROORGANISMS

	Temperature		
	Minimum	Optimum	Maximum
	°C.	°C.	°C.
Fungi (146, 295)			
Aspergillus candidus	3–4	20–24	42
A. flavus	6–8	36–38	44–46
A. herbariorum	4–5	27–30	40
A. nidulans	6–8	25–30	48–50
A. niger	6–8	35–37	46–48
A. oryzae	7–9	35–37	45–47
A. repens	4–5	26–30	38–40
A. versicolor	4–5	25–30	38–40
Rhizopus nigricans	5–6	26–29	32–34
R. oryzae	7–9	36–38	43–45
Monilia candida	4–6	....	42–43
Oidium lactis	0.5	....	37.5
Bacteria (58)			
Bacillus subtilis	6	30	50
B. mycoides	10–12	28–31	38–41
B. megaterium	....	28–35	40–45
Aerobacter rancens	6–7	34	42
Escherichia coli	10	30–37	45
Sarcina maxima	15	30	40
Proteus spp.	....	37	
Pseudomonas fluorescens	...	20–25	.
P. putrificus	....	21	...
P. putida	....	25	....
Lactobacillus plantarum	15–18	41–42	48–50
L. brevis	15	30	37

temperatures for growth are affected by moisture, availability of nutrients, oxygen concentration, and other factors. Except for *Endoblastomyces thermophilus,* which grows at a maximum temperature of 76°C., fungi generally have lower maximum growth temperatures than bacteria or actinomycetes. Fungi may be active in decomposing plant materials up to temperatures of 65°C., while some bacteria and actinomycetes are active to 75°C. (268, 416).

Microorganisms produce heat as a product of their metabolism (21, 27, 329, 386). The amount they produce depends on their metabolic activity, which is influenced by such factors as temperature, moisture (12, 163, 181, 321), oxygen concentration (69), nutrients (17, 68, 130), and age of cells (21, 423). The highest temperature that any one organism can produce under adiabatic conditions is the maximum temperature at which that organism can grow (Table IX).

Microorganisms perish at temperatures outside the range for growth. They die rapidly when the temperatures are above the maximum (107,

TABLE VII

CARDINAL GROWTH TEMPERATURES OF SOME THERMOPHILIC MICROORGANISMS

	Temperature		
	Minimum	Optimum	Maximum
	°C.	°C.	°C.
Fungi			
Thermoascus aurantiacus (268)	35	40–46	55
Thermoidium sulfureum (289)	29–30	35–45	55
Thermomyces lanuginosus (268)	30	40–57	60
Chaetomium thermophile (228)	30–35	50	55–58
Anixia spadicea (289)	27	....	58
Mucor pusillus (268)	21	40–46	56
M. pusillus (295)	6–8	37–40	56–60
Mucor corymbifer (269)	....	....	near 60
Rhizopus chinensis (445)	10	....	52
Rhizopus humilis (445)	....	....	50
Penicillium sp. (269)	35	....	60
Aspergillus fumigatus (295)	10–12	37	57–58
Endoblastomyces thermophilus (292)	20	42–44	76
Penicillium duponti (400)	25	45–50	60
Bacteria			
Lactobacillus lactis (58)	18–22	40	50
Lactobacillus delbrueckii (58)	....	45	
Lactobacillus thermophilus (58)	30	50–63	65
Bacillus subtilis (136)	....	30–37	50–56
Bacillus brevis (136)	.....	30	43–54
Bacillus calfactor (268)	30	50–60	70
Clostridium perfringens (58)	....	35–37	50
Clostridium roseum (58)	8	37	62
Actinomycetes			
Actinomyces thermophilus (289)	30	40–59	62
Actinomyces thermofuscus (417)	28	...	near 65
Micromonospora spp. (417)	...	....	65

162, 268, 269) and slowly when the temperatures are below the minimum (120, 318). Vegetative cells of high-moisture content die more rapidly than cells or spores of low-moisture content. At subminimal temperatures above 0°C., vegetative cells of some thermophiles (Table X) and mesophiles die within a short time, depending on the temperature. At subminimal temperatures below 0°C., vegetative cells and moist spores of psychrophiles, mesophiles, and thermophiles die within a short or long time, depending on the duration of cooling and on whether ice crystals are formed outside or inside the cells (15, 72, 240). At supramaximal temperatures, fungal and bacterial vegetative cells, and moist spores perish within a short or long time, depending upon the temperature (162, 268). Most fungi and bacteria die within 10 minutes at 55°C., while few survive 65°C. for the same length of time (287); the few that survive are thermophiles.

TABLE VIII

MINIMUM AND MAXIMUM GROWTH AND SPORULATION TEMPERATURES OF SOME MICROORGANISMS

	Growth		Asexual Sporulation		Sexual Sporulation	
	Min.	Max.	Min.	Max.	Min.	Max.
Fungi	°C.	°C.	°C.	°C.	°C.	°C.
Aspergillus repens (206)	7–8	37–38	8–9	35–36	....	33–34
Sporodinia grandis (206)	1–2	31–32	5–6	29–30	5–6	27–28
Mucor racemosus (206)	4–5	32–33	6–7	30–31	....	....
M. racemosus (146)	0.5	32–33	0.5–3	31–32	....	....
M. alpinus (146)	0.5	29–31	0.5–1	27	3	25–26
M. neglectus (146)	3	33	3–4	29	3–4	32
Rhizopus arrhizus (426)	7	41	15	37	....	....
R. oryzae (426)	11	42	15	37	....	....
R. nigricans (426)	1.5	31	10	30	....	....
R. nigricans (445)	....	35	....	30	....	....
R. oryzae (445)	....	45	....	35	....	....
R. chinensis (445)	....	52	....	45	....	....
Saccharomyces cerevisiae I (146)	1–3	40	....	....	11–12	36–37
S. pastorianus I (146)	0.5	34	....	....	3–4	29–30
S. ellipsoideus I (146)	0.5	40–41	....	....	7.5	30–31
S. marxianus (146)	0.5	46–47	....	....	8	32
S. anomalous (146)	0.5–1	37–38	....	....	6–7.5	32–32.5
Bacteria						
Bacillus anthracis (340)	8	....	....	....	10	....
B. subtilis (340)	12	....	....	....	14	....
B. tumescens (340)	10	....	....	....	11	....
B. mycoides (171)	12	38	....	....	10	35
B. mycoides (38)	....	30–35	....	....	....	30–35
B. megaterium (38)	....	45–50	....	....	....	35–40
B. subtilis (38)	....	55–60	....	....	....	55–57
B. calidus (38)	35–40	70–73	....	....	40–45	70–73
B. tostus (38)	35–40	74–75	....	....	35–40	73–74

Dry spores of many fungi may survive 87°C. for 30 minutes while only a few survive 121°C. for the same length of time. Among these few are (397): *Penicillium chrysogenum, P. cyclopium, P. divaricatum, P. oxalicum, P. spinulosum, P. viridicatum, Aspergillus flavus, A. niger* var. *altipes, A. cinnamomeus, A. fuscus, Circinella umbellata,* and *Mucor racemosus.* Bacterial spores, which are more resistant to moist heat than fungus spores, may withstand 95°C. for 45 minutes (225) or even 100°C. for as long as 20 hours (38). Their heat resistance appears to be correlated with the maximum temperature at which they grow (38, 225) and with the percentage of bound water in the spores (125).

Moisture. Water contributes to the chemical and physical structure of microorganisms and is involved in the cellular work of metabolism and translocation of materials. Small portions are tightly bound by the protoplasm; the remainder is movable and may be depleted or increased,

TABLE IX

RELATION BETWEEN DEATH TEMPERATURES AND MAXIMUM HEATING TEMPERATURES OF DIFFERENT MICROORGANISMS

(After Miehe, 269, and Wedberg and Rettger, 423)

	Death Temperatures of Vegetative Hyphae	Maximum Heating Temperatures
	°C.	*°C.*
Aspergillus fumigatus	above 60	54, 57
A. niger	50–55	49.5, 52, 53.5
Mucor corymbifer	about 60	56.5
Penicillium glaucum	40–45	41
Penicillium sp.*	above 65	61
Rhizopus nigricans	below 40°C. for 4 hrs.	38, 35
Thermoidium sulfureum	50–60	58
Thermomyces lanuginosus	60–65	61, 62.5
Yeast	50	45.5, 50.5
Actinomyces thermophilus	60–65	60, 63, 63
Achromobacter sp.	45.5	45.5
Aerobacter aerogenes	45.5–46.5	47.0–54.5
Bacillus coli-foenicola	40	38
B. calfactor	above 70	51, 67.7, 74, 68, 68.1
B. subtilis	50.5–57.5	53.0–60.5
B. vulgatus	54.5	55.5–56.0
Proteus sp.	45.5	44.5–47.5

*Similar to *Thermoascus aurantiacus*.

TABLE X

DEATH TIME OF YOUNG VEGETATIVE CELLS OF THERMOPHILIC MICROORGANISMS AT VARIOUS SUBMINIMAL TEMPERATURES

(After Noack, 289)

	Minimum Growth Temperature	Temperature Range, °C. 5-6	10-11	15-17	20-24
	°C.	*Days*	*Days*	*Days*	*Days*
Anixia spadicea	27	2–4	11–12	20–22	28–29
Mucor pusillus	21	3–6	11–12	22–24	....
Thermoascus aurantiacus	35	2–4	7–9	11–14	22–24
Thermoidium sulfureum	29–30	18–20	24–27	31–34	42–48
Thermomyces lanuginosus	30	28–33	32–36	42–45	267
Actinomyces thermophilus	30	14–18	14–18	27–30	32–35
Bacillus calfactor	30	1⅓–1⅔	2	....	2–2½

depending on the vapor pressure difference between it and the water in the environment.

Microorganisms are classified as hydrophytes, mesophytes, or xerophytes on the basis of their minimum moisture requirement for growth (66, 153, 296, 421, 422). They are hydrophytes when their minimum requirement is 90% relative water-vapor pressure or greater, mesophytes when the minimum requirement is between 80 and 90%, and xerophytes when the minimum requirement is less than 80%. Hydrophytes grow best near 100% relative vapor pressure, mesophytes grow best at 98 to 100% relative vapor pressure, and xerophytes grow best at 95 to 100% relative vapor pressure, or at some lower value (153).

Bacteria are hydrophytes, so far as is known (66, 153, 306, 421). Species, and strains within species, of eubacteria differ in their minimum moisture requirements—from 90.5% relative vapor pressure for *Micrococcus roseus* to 99% for *Bacillus mycoides* (Table XI). Actinomycetes have a minimum water requirement as low as 90 to 93% relative water-vapor pressure (306).

TABLE XI

MINIMUM RELATIVE WATER-VAPOR PRESSURES SUPPORTING GROWTH OF VARIOUS SPECIES AND STRAINS OF BACTERIA

(Mainly after Burcik, 66)

	Relative Vapor Pressure		Relative Vapor Pressure
	%		%
Bacillus mycoides	99, 97	*Bacillus vulgare*	96, 94
Pseudomonas pyocyanea	99, 98.5, 95	*Bacterium coli*	96, 93.5
Bacillus luteus	98.5	*Bacillus subtilis*	95
Bacillus asterosporus	98.5	*Bacterium prodigiosum*	94.5
Bacillus radicicola	98, 96.5	*Bacterium aerogenes*	94.5
Azotomonas insolita	97	*Mycobacterium siliacum*	94
Erwinia amylovora (352)	96	*Pseudomonas iniqua*	94
Pseudomonas tumefaciens	96	Yellow *Sarcina* sp.	93, 91.5
Bacillus mesentericus	95.5	*Micrococcus roseus*	90.5

Bacterial colonies grow faster on a solid or semisolid substrate in a moist atmosphere than in a dry atmosphere (352, 405, 436). The minimum moisture requirements appear to be affected by the availability and kinds of nutrients in the substrate (352). They survive longer at subminimal relative water-vapor pressures when the temperatures are

relatively low (299) than when they are high. They also survive longer when encapsulated in slime (328).

Yeasts and yeastlike fungi appear to be hydrophytes or mesophytes. Their minimum water requirement ranges from 88 to 96% relative vapor pressure (Table XII).

TABLE XII

MINIMUM RELATIVE WATER-VAPOR PRESSURES SUPPORTING GROWTH OF YEASTS AND YEASTLIKE FUNGI
(After Burcik, 66)

	Relative Vapor Pressure		Relative Vapor Pressure
	%		%
A yeast, unidentified	96	*Oospora lactis*	89.5
Torula utilis	94	*Saccharomyces cerevisiae*	89.5
Schizosaccharomyces Jörgensohnii	93	*Rhodotorula* sp.	89
Willia sp.	91	*Endomyces magnusii*	88.5
Mycoderma cerevisiae	90	*Endomyces vernalis*	88
Zygosaccharomyces polymorphus	90	*Willia anomala*	88

Molds are hydrophytes, mesophytes, or xerophytes. Their minimum water requirement for spore germination ranges from 62 to 99% relative vapor pressure, as shown in Table XIII. Members of the Aspergillus glaucus group, *Aspergillus candidus, A. versicolor,* and *A. sydowi*, are xerophytes, while other Aspergillus species, some Penicillium species, several members of the Mucorales, *Alternaria citri, Cladosporium herbarum, Ustilago avenae,* and *Trichoderma* sp. are mesophytes. Many members of the Mucorales, several species of Penicillium, and most phytopathogenic fungi are hydrophytes. According to Blochwitz (40, 41, 42), members of the order Mucorales and the genus Penicillium are hydrophytes, colonizing plant materials in the tropics and subtropics following rains, while certain members of the genus Aspergillus are xerophytes, growing on exposed products in drier climates.

The minimum moisture requirements of individual spores in a single mold population are normally distributed. One or several spores have the lowest or highest minimum water requirement, while the remainder have intermediate minimum water requirements. Data for hydrophytes (75, 85, 277, 325) show a sigmoid distribution of the percentage of spores germinating between the minimum and 100% relative vapor pressure. Observation on xerophytes suggest a similar distribution (365).

TABLE XIII

MINIMUM RELATIVE WATER-VAPOR PRESSURES SUPPORTING SPORE GERMINATION OF DIFFERENT FUNGI

Relative Water-Vapor Pressure	Fungi	Fungi
%		
99	*Venturia inaequalis* (85)	
98	*Chaetocladium* sp. (418) *Puccinia graminis* (85)	
96	*Cladosporium fulvum* (285) *Phycomyces nitens* (418) *Thielaviopsis* sp. (129)	
94	*Alternaria tenuis* (418) *Botrytis cinerea* (325) *Cladosporium herbarum* (325) *C. fulvum* (143) *Colletotrichum falcatum* (75) *C. lindemuthianum* (75) *Cunninghamella elegans* (418) *Gloeosporium tabacum* (75)	*Helicostylum pyriforme* (418) *Mucor* sp. (418) *Phycomyces nitens* (421) *Phyllosticta cajani* (75) *Piltaria anomala* (418) *Thamnidium elegans* (418) *Ustilago hordei* (85) *U. avenae* (85)
92	*Botrytis cinerea* (365) *Mucor* sp. (365) *M. plumbeus* (418) *M. racemosus* (295) *M. spinosus* (365)	*Penicillium brevicaule* (418) *Rhizopus* sp. (418) *R. nigricans* (295) *Trichoderma lignorum* (295) *Zygorhynchus exponens* (418)
90	*Absidia glauca* (418) *Acrothecium* sp. (129) *A. penniseti* (75) *Alternaria citri* (407) *A. brassicae* (75) *A. solani* (205) *Botrytis* sp. (325) *Cephalothecium roseum* (418) *Cladosporium* sp. (129)	*C. fulvum* (143) *Cladosporium herbarum* (325) *Helminthosporium nodosum* (277) *H. frumentacei* (75) Penicillium glaucum (325) *Rhizopus* sp. (421) *Scopulariopsis brevicaule* (129) *Stemphylium* sp. (129) *Syncephalastrum cinereum* (418)
88	*Aspergillus niger* (295) *Cladosporium herbarum* (365) *Mucor racemosus* (350) *Penicillium palitans* (350)	*Penicillium rugulosum* (350) *Ustilago avenae* (153) *Trichoderma* sp. (129)
86	*Aspergillus flavus* (129) *A. fumigatus* (129, 295) *A. glaucus* (418, 421) *A. nidulans* (129) *A. niger* (129) *A. ochraceus* (129) *A. oryzae* (129) *A. sulphureus* (418) *A. tamarii* (129)	*Aspergillus terreus* (129) *Penicillium* sp. (129, 418) *P. duclaux* (129) *P. expansum* (129) *P. italicum* (295) *P. rugulosum* (365) *P. spinulosum* (129) *Phycomyces nitens* (153)
84	*Alternaria citri* (407) *Aspergillus niger* (365) *Penicillium chrysogenum* (350) *P. cyclopium* (365)	Penicillium glaucum (421) *Rhizopus nigricans* (153) *Sporodinia grandis* (153)

TABLE XIII (Continued)

MINIMUM RELATIVE WATER-VAPOR PRESSURES SUPPORTING SPORE GERMINATION OF DIFFERENT FUNGI

Relative Water-Vapor Pressure	Fungi	Fungi
%		
82	*Aspergillus nidulans* (365) *Penicillium chrysogenum* (129, 141, 295)	*Penicillium expansum* (295) *P. pheo-janthinellum* (365) *P. wortmanni* (365)
80	*Aspergillus chevalieri* (129) *A. flavus* (295) *A. nidulans* (295) *A. niger* (350) *A. repens* (129) *A. ruber* (129) *A. versicolor* (129)	*Aspergillus sydowi* (129) *Penicillium citrinum* (129) *P. fellutanum* (365, *P. rugulosum* (295) *P. sartoryi* (365) *P. spinulosum* (295)
78	*Aspergillus sydowi* (365, 387) *A. versicolor* (365) Penicillium glaucum (153)	
76	*Aspergillus candidus* (129, 295) *A. herbariorum major* (129) *A. versicolor* (295)	
75	*Aspergillus amstelodami* (365) *A. candidus* (295, 365)	*Aspergillus chevalieri* var. *intermedius* (365) *A. restrictus* (365)
74	Aspergillus glaucus (153)	
73	*Aspergillus chevalieri* (365)	
72	*Aspergillus amstelodami* (350) *A. candidus* (350)	
71	*Aspergillus echinulatus* (365) *A. repens* (365)	
70	Aspergillus glaucus (374) *A. ruber* (365)	
67	*Aspergillus herbariorum* (295)	
65	*Aspergillus chevalieri* (295)	
62	*Aspergillus echinulatus* (365)	

Mold spores have different minimum water requirements at different temperatures. Their minimum is lowest at the optimum temperature for growth, and highest near the minimum and maximum temperatures at which growth is possible. This is shown in Table XIV.

Mold spores also have different minimum water requirements depending on the presence or absence of nutrients (62, 365, 366, 407). They require the least amount in the presence of nutrients and most

TABLE XIV

MINIMUM RELATIVE WATER-VAPOR PRESSURES SUPPORTING GERMINATION OF FUNGUS SPORES AT DIFFERENT TEMPERATURES[a]

Fungus	Temperature, °C.											
	5°	10°	11.5°	15°	18°	20°	25°	30°	35°	37°	40°	42.5°
Alternaria citri[b] (407)	97.1	95.6	....	....	94.2	....	90.8	*89.3*	....	92.6	....	....
Alternaria citri (407)	94.2	90.8	....	....	87.6	....	85.8	*83.3*	....	87.6	....	....
Aspergillus glaucus (374)	....	....	77	75	....	73	....	*70*	75	....	85.5	98.0
Aspergillus glaucus (153)	....	....	....	....	....	73.3	....	70.8	....	....	....	....
Aspergillus sydowi (387)	....	....	....	....	....	85	....	77	....	....	85	....
Oidium lactis (153)	....	92.6	....	....	....	*90.0*	....	91.8	....	....	....	....
Phycomyces nitens (153)	....	89.2	....	....	....	*86.6*	....	90.6	....	....	....	....
Trichoderma lignorum[b] (407)	....	95.6	....	....	92.6	....	*90.8*	94.2	....	95.6	....	....

[a] The lowest minima are in italics.
[b] Spores germinated on glass; others on agar or gelatin media.

in the absence of nutrients, as may be seen for *Alternaria citri* in Table XIV. Consequently, they germinate at lower vapor pressures and over wider ranges of temperature when suitable nutrients are present than when they are absent.

As Figure 3 shows, the rate at which mold spores germinate is hyperbolically slower as the relative water-vapor pressure is farther from the optimum (153, 365). They germinate within one day under optimum moisture conditions but require several months to one or more years near minimum moisture conditions (366).

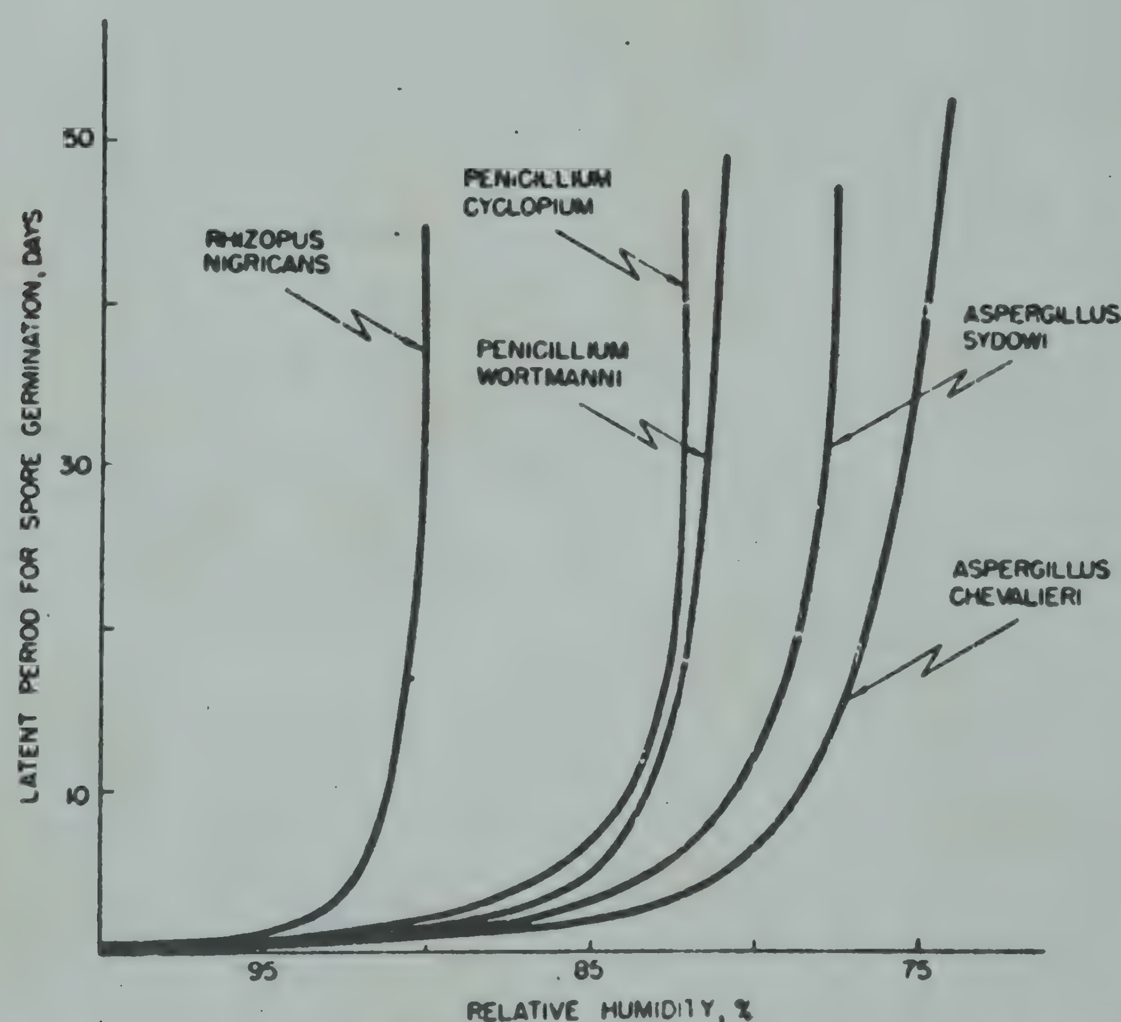

Fig. 3. Germination time (latent period) of different mold spores at different relative humidities (adapted from Snow, 365).

Mold spores slowly perish in atmospheres of subminimum moisture content. They perish faster when temperatures are high than when they are low. Spores of *Aspergillus ruber, A. echinulatus, A. repens,* and *A. chevalieri* perished within one year at 60% relative water-vapor pressure and 25°C. (365). Chlamydospores of *Urocystis tritici* died within one year at 89.0% and 72.5% relative vapor pressure, within 2 years at 64% relative vapor pressure, within 3 years at 50% relative vapor pressure, and within 10 years at 33.5%, 31.2%, 11.9%, and 0.1% relative vapor pressure (291). Conidia of *Helminthosporium oryzae* perished within 6 months at 45%, 70%, and 90% relative water-vapor pressure when the temperatures were at the upper end of the range 10° to 31°C.,

but survived at 20% relative water-vapor pressure over these same temperatures (294). Uredospores of *Puccinia graminis tritici* on excised wheat leaves perished faster at relative vapor pressures progressively higher or lower than 49%, and faster at 25°C. than at lower temperatures (300, 301). At subminimum relative water-vapor pressures, conidia of *Penicillium chrysogenum* survived for 38 days or more when the temperatures were favorable for growth (10° to 35°C.). Their survival period was shorter at higher temperatures and at these higher temperatures they died faster as the water-vapor pressure increased from 0 to 100% (141). Individual spores of each population died at rates that were normally distributed. Their death was gradual, exhibiting phases of slower germination and weakened germ-tube production (141).

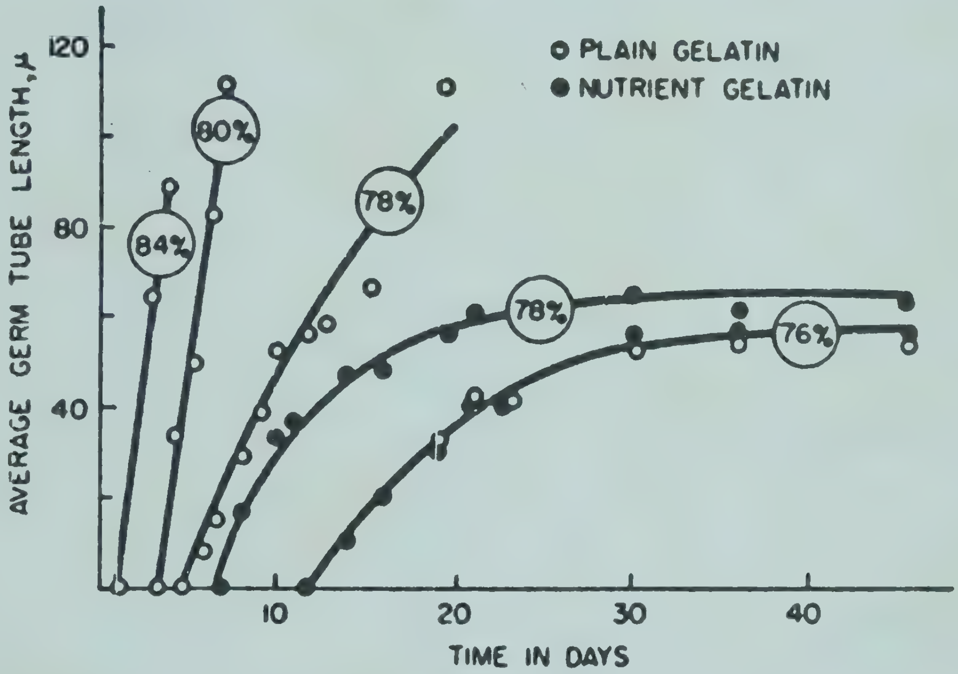

Fig. 4. Germ tube elongation rates of *Aspergillus repens* at different relative humidities when grown on plain gelatin and on nutrient gelatin (after Snow, 365).

Germ-tubes elongate (Fig. 4) at constant rates when relative water-vapor pressures approach the optimum and at declining rates as the relative water-vapor pressures approach the minimum (365). The presence of available nutrients establishes constant growth rates when moisture supplies are adequate but not when they approach the limiting value.

Molds develop abnormal vegetative forms when water is restricted. Their hyphae become swollen, twisted, and abundantly divided by cross-walls. They lose their power to advance through substrates (365). In another way, *Ustilago avenae* changed from a yeastlike form at 100% relative water-vapor pressure to a mycelial form at 96 to 98% relative water-vapor pressure, producing cross-walls in the older hyphae (153). At 90% relative water-vapor pressure it produced filaments of oval cells. Similarly, a yeast changed to a myceliumlike form at 98% relative

water-vapor pressure and to a mycelium at 90% relative water-vapor pressure (421).

Molds sporulate over narrower ranges of relative water-vapor pressure than those which allow growth to take place (Table XV). They take longer to sporulate at lower than at higher moisture levels (Table XVI), and sporulation occurs sooner and at lower moistures in the presence of readily available nutrients than in their absence (Table XVI).

TABLE XV

MINIMUM RELATIVE WATER-VAPOR PRESSURES FOR GROWTH AND SPORULATION OF DIFFERENT FUNGI
(After Panassenko, 295)

	Growth	Asexual Sporulation	Sexual Sporulation
Aspergillus candidus	75	80	..
A. chevalieri	65	73–75	86
A. flavus	80	85	.
A. fumigatus	85	90	..
A. herbariorum	67	75	86
A. nidulans	80	85	95
A. niger	88–89	92–95	..
A. versicolor	75	80	..
Mucor racemosus	92	95	..
Penicillium chrysogenum	83	85	..
P. expansum	82	85	..
P. italicum	87	89	..
P. rugulosum	80	85	..
P. spinulosum	80	84	..
Rhizopus nigricans	92–94	96	..
Trichoderma lignorum	92	95	..

Other effects of moisture on sporulation that have been observed are as follows: germ-tubes of *Cladosporium fulvum* changed to conidia when exposed to between 60 and 80% relative water-vapor pressure (193); *Helminthosporium sativum* produced smaller spores at lower than at higher relative water-vapor pressures (372); maximum sporulation of mature cultures of *Alternaria solani* on agar media took place at 84% relative water-vapor pressure at 13°C., and near 100% relative water-vapor pressure at 26°C. (205); *Mucor racemosus, Cladosporium herbarum*, and *Penicillium flavo-glaucum* formed conidia at 0°, 3°, and 6°C. only at high relative water-vapor pressures (343).

Oxygen. Microorganisms are subdivided, according to their oxygen requirement, into anaerobes and aerobes as main groups. Bacteria are represented in both these categories. Some anaerobes, such as *Clostridium butyricum*, may grow at maximum oxygen concentrations as high as 0.27% by volume and withstand exposure to 0.69% oxygen for 10 days without injury (83), while others may have lower or slightly higher

maximums (9, 83, 221). Aerobes such as sporulating *Bacillus subtilis, B. megaterium,* and *B. mycoides* grow at minimum oxygen concentrations near 0.8% and sporulate at slightly higher oxygen concentration (237, 266, 444). Bacillus species require more oxygen for cell multiplication than do the species of the family Pseudomonadaceae; the latter require more than the species of the family Enterobacteriaceae, while species of the genus Streptococcus require the least amount (319). The minimum

TABLE XVI

NUMBER OF DAYS TO APPEARANCE OF GROWTH AND SPORULATION OF ASPERGILLUS REPENS UNDER ADEQUATE AND DEFICIENT NUTRIENT SUPPLY

(After Snow, 365)

Relative Water-Vapor Pressure	Spore Germination		Asexual Sporulation		Sexual Sporulation	
	N[a]	P[b]	N	P	N	P
%						
100	1	1	2	3	4	12
95	1	1	2	4	4	19
93	1	1	2	5	6	56
90	1	1	3	7	7	*
88	2	2	4	10	10	*
86	2	7	5	25	19	*
84	2	7	7	57	*	*
82	3	7	12	*	*	*
80	4	7	13	*	*	*
78	6	8	30	*	*	*
76	14	16	*	*	*	*

[a] Nutrient gelatin medium.
[b] Plain gelatin medium.
* No sporulation in 56 days.

oxygen requirements, however, are influenced by the availability of nutrients. Aerobic bacteria grow hyperbolically more slowly as the oxygen concentration approaches the minimum requirement (338).

Actinomycete genera Streptomyces and Nocardia are aerobes (333, 415). Yeasts (179, 208) and some Mucors (186, 424) are moderate aerobes that can grow for a short time under seemingly anaerobic conditions but do not sporulate. They soon die when the oxygen tension approaches zero.

The majority of the fungi, including thermophilic fungi (290), are strong aerobes. They fail to sporulate (224, 386), their spores fail to germinate (62, 105, 190, 224, 252, 305, 384), and their mycelium fails to grow when the oxygen concentration is below a minimum which is yet adequate for yeast growth. Although mycelium cannot grow, it respires (94, 212, 213, 214, 408) and remains viable (101) for a short time under

subminimum oxygen supply; under the same conditions spores remain viable longer than mycelium. Molds grow at nearly constant rates over wide ranges of oxygen concentration (93, 194, 270, 384) and at hyperbolically slower rates as the oxygen concentration approaches the minimum requirement (270, 336, 388). Their threshold oxygen requirement for growth is illustrated in Table XVII. The requirement is raised in the absence of suitable nutrients (62, 305).

TABLE XVII

OXYGEN CONCENTRATION IN WATER NECESSARY FOR GROWTH OF SEVERAL FUNGI[a]
(Adapted from Miller and Golding, 270)

Fungus	Minimum	Optimum
	Vol. %	*Vol. %*
Oospora lactis	near 0	0.03
Aspergillus flavus	0.002	0.038
Aspergillus niger	0.006	0.056
Penicillium expansum	0.003	0.056
P. notatum	0.006	0.08
P. roqueforti	0.008	0.078

[a] Doubt (444) has been cast on the reliability of older data (94, 307, 425) not included here.

Molds grow in a yeastlike manner when oxygen is a limiting factor (126, 186, 224), as they do under moisture deficiencies.

Activity of Microflora in Stored Grain and Grain Products

As may be inferred from the preceding outline, microorganisms either grow or slowly perish in stored grain and grain products, depending on the environment. One or more of them may grow somewhere between 62% and 100% relative humidity, between −8° and 75°C., and between 0% and over 21% oxygen concentration. For any one of these extreme possibilities to be realized the other two factors must be optimum. If they are not, the allowable limits for the third factor must be reduced. Because many molds grow at lower relative water-vapor pressures than bacteria, molds are the important agents of deterioration in grain and grain products at below 90% relative humidity, provided, of course, that temperatures and oxygen concentrations permit their growth. When the relative humidity is higher, bacteria become as important as molds. Bacteria, however, may also be important at seemingly lower moistures when the metabolic water from molds (284) creates pockets of higher moistures.

Molds. Growth of molds in grain (Fig. 5) and grain products may be followed (1) by watching for first signs of mycelium formation and

sporulation, and (2) by using cultural methods to determine qualitative and quantitative changes in the composition of the mold flora. Accelerated respiration, viability losses in grains, and quantitative changes in the chemical composition of grain and grain products may also be measures of mold growth under low moisture conditions, but when the moisture is high, bacteria contribute to these changes. Mustiness, which is commonly associated with mold growth, is of uncertain origin (278). It may also be due to actinomycetes (184) and eubacteria (236, 411).

Fig. 5. (A) A member of the Aspergillus glaucus group growing and sporulating on an ear of corn (courtesy of J. C. Gilman); (B) a species of *Aspergillus* growing and sporulating mostly from the germ of a surface-disinfected kernel of sick wheat (courtesy of C. M. Christensen).

Visual detection of mycelium formation is a better method for establishing initial mold growth than is visual detection of sporulation (Table XVIII). And, as shown in Table XIX, it is better than the plate culture method of mold count, which reveals mold growth mainly when sporulation is attained. The plate culture method, which is widely used to evaluate the qualitative and quantitative changes in mold flora, is selective for molds that grow on the culture medium used (Table XX), and for molds having intermediate or high sporulation tendencies. Different culture media and methods of measuring mycelium growth should be used to evaluate better the changes in the mold flora.

TABLE XVIII

NUMBER OF DAYS TO FIRST APPEARANCE OF MOLD MYCELIUM ON DIFFERENT FEEDING STUFFS AND NUMBER OF DAYS THEREAFTER TO BEGINNING SPORULATION
(After Snow, Crichton, and Wright, 366)

Feed Stuff	Fungus Development	Relative Humidity, %									
		100	90	85	80	77	75	72	71	67	65
Locust beans	Mycelium	2	3	5	9	19	35	82	118	314	861
	Sporulation	2	3	4	7	22	29	59	32	...	...
Bran	Mycelium	2	4	5	9	21	35	101	129	525	...
	Sporulation	1	2	4	9	20	38	65	46	...	...
Oats	Mycelium	2	3	5	9	19	32	141	175	961	...
	Sporulation	1	2	8	12	50	49	720	686	...	...

TABLE XIX

RELATION BETWEEN MOLD COUNT AND TIME OF APPEARANCE OF MOLD GROWTH AND SPORULATION IN DRIED HAY STORED UNDER DIFFERENT MOISTURE CONDITIONS
(Adapted from Wright, 443)

Relative Humidity	Moisture Content	First Evidence of Mycelial Stage		First Evidence of Sporulation Stage		Period Following Sporulation [b]	
%	%	Days Stored	Mold Count [a]	Days Stored	Mold Count	Days Stored	Mold Count
85	24	8	400	13	850,000	19	19,000,000,000
80	19	18	100	25	1,130,000	37	325,000,000
78	18	21	300	37	100,000	56	11,300,000,000
76	17	37	650	56	30,000	89	1,080,000,000
74	16	61	450	98	124,000	147	100,000,000
72	15	133	200	230	44,400	520	380,000
70	14	303	100	[d]	....	520	900
67	13	[c]	....	[d]	....	520	....

[a] Initial mold count was 440.
[b] Half again as long as the number of days required for sporulation to begin.
[c] Mycelium not evident in 520 days.
[d] Sporulation not evident in 520 days.

Molds slowly perish in stored grain and grain products when moisture is subminimum for growth. A 90% decline in mold count has been observed in cornmeal stored for 2 months (399), while a 50% decline has been observed in flour with 14 and 15% moisture, after storage for 250 days at 15° and 20°C. (20). Dungan and Koehler (104) noted that *Gibberella zeae, Nigrospora oryzae, Diplodia zeae, Cephalosporium acremonium,* and *Fusarium moniliforme* perished in corn within 2 to 9

TABLE XX

NUMBER OF COLONIES OF FIVE MOLDS OBTAINED FROM A SAMPLE OF MOLDY CORN WHEN THE LATTER WAS TESTED ON DIFFERENT CULTURE MEDIA (After Bottomley, Christensen, and Geddes, 53)

Agar Medium	Aspergillus glaucus	*Aspergillus flavus*	*Aspergillus tamarii*	*Aspergillus candidus*	*Penicillium* sp.
Czapek-Dox	0	65	42	0	16
Malt-salt-sucrose	57	55	46	0	21
Malt-salt-boric acid	58	57	42	49	43

years, depending on the fungus. Some of the kernels still retained their viability when the observations were concluded. Similarly in barley, Shands (351) noted that *Gibberella zeae*, *Alternaria* sp., *Helminthosporium* sp., Penicillium spp., *Nigrospora* sp., and Fusarium spp. perished within 30 to 63 months, while miscellaneous fungi (and bacteria) survived the observation period. The percentage of sterile barley kernels increased from near 0% at 6 months' storage, to about 30% after 15 months' storage, and to near 100% after 63 months' storage.

Minimum moisture levels required for mold growth in stored grain and grain products depend on temperature, the nutritive value of the material to the molds, and, possibly, oxygen supply. The percentages of moisture required appear to be lower at optimum than at suboptimum temperatures for growth on wheat (379, 381), flour (20), bran (20), and other materials (366). Molds will grow at lower moisture levels in starch to which protein has been added than in starch or protein alone (366); in starch or protein than in fiber (366); and in finely ground than in coarsely ground materials (366). A moisture content equivalent to a relative vapor pressure of 65% has been suggested as borderline for 2 to 3 years' storage of grain and grain products held at 60° to 70°F. A moisture level in the substrate in equilibrium with air at 72% relative vapor pressure has been suggested as borderline for 3 months' storage at these same temperatures (363). The moisture values in some grain and grain products that correspond to these relative vapor pressures are shown in Table XXI. These moisture values are similar to those suggested for the safe storage of wheat (8, 10, 117, 175, 216, 218, 220, 341, 380, 403), shelled corn (349), and cereal feeds (362); but these suggested moisture levels are not always low enough to prevent deterioration of the products under certain conditions (169, 197, 198, 245, 350).

Molds appear sooner in grain and grain products as the moisture content increases above the minimum and as optimum temperatures and oxygen concentrations (20, 52, 350, 366) are approached. They

TABLE XXI

APPROXIMATE MOISTURE CONTENT[a] OF GRAIN AND GRAIN PRODUCTS IN EQUILIBRIUM WITH 65% AND 75% RELATIVE HUMIDITY

(After Snow, 363)

Grain or Grain Product	Relative Humidity 65%	75%
	%	%
Barley	13.6	14.8
Bran	12.8	14.4
Oats	13.4	14.5
Maize	13.7	14.8
Middlings	13.1	14.1
Wheat	14.6	15.7

[a] Dry weight basis.

appear at a hyperbolic (20, 350) or logarithmic rate (366) sooner as the relative water-vapor pressures approach their optimum. They appear sooner (a) on dead or weakened grains than on grains capable of germinating to produce vigorous normal seedlings (175); (b) on live grains with broken or cracked pericarps than on live grains with unbroken pericarps (3, 175, 263, 267, 278, 420); (c) on the germ end of wheat (271) and corn kernels (209, 248, 350) than on other parts of these kernels; (d) on barley kernels with pedicels detached than on those with pedicels attached (175); (e) on wheat varieties with protruding, long embryos than on wheat varieties with pericarp-enclosed, short embryos (262); (f) on bran than on flour (20) or oats (366); (g) on starch, protein, starch plus protein, and starch plus fiber than on fiber (366); (h) on starch and starch plus protein than on protein (366); and (i) on finely ground than on coarsely ground materials (366). Morgenthaler (278) believed the matting of wheat into clumps by molds was due to growth of molds from pericarp injuries which allowed access to nutritive materials in the endosperm. He frequently found healthy, unattacked kernels free of pericarp injuries occluded among the matted, injured, mold-permeated, dark-brown kernels.

Increases in moisture levels (366), temperatures (366), and possibly oxygen concentrations, above the minimum requirements, cause molds to sporulate sooner in grain and grain products. They sporulate sooner on bran than on oats, sooner on finely ground than on coarsely ground materials, sooner on protein than on starch, starch plus protein, or starch plus fiber (366), and sooner on protein, starch, starch plus pro-

tein, and starch plus fiber, than on fiber (366). At 75 to 100% relative humidity they sporulated within 1 or 2 days after the mycelium first appeared on a protein, while they sporulated within 1 to 126 days after the mycelium first appeared on a starch (366).

Molds also grow faster and sporulate more abundantly as the relative water-vapor pressure approaches 95 to 100%, the temperature approaches 28° to 32°C. and the oxygen concentration exceeds a level of about 1%. As revealed by mold count, their numbers increased: (a) with increases in temperature when wheat containing 22.8% moisture was stored 3 months at −5°, 0°, 5°, 10°, and 20°C. (216), and when wheat heated spontaneously to as high as 54°C. (79); (b) with increases in moisture when wheat of 17.9 to 35.5% moisture was stored 10 days at 30°C. (272), and when wheat of 15.4 to 38.6% moisture was stored 20 days at 30°C. (273); (c) with increases in moisture and temperature when flour containing 16.5%, 17.0%, and 19.6% moisture was stored 250 days at 10°, 15°, and 20°C. (20); and (d) with increases in moisture and oxygen concentration and decrease in temperature when corn containing 17.4 to 31.2% moisture was stored 12 days under 0.1 to 21% oxygen concentrations at 25° to 45°C. (52). Their numbers increased with increases in moisture when corn of 24%, 27%, and 30% moisture was stored 12 days in sealed containers at 30°C. (53), and with increase in temperature when wheat of 20% moisture was stored 15 days in rubber-stoppered bottles at 20° and 37°C., although there was no increase at 50°C. (274).

The kinds of molds that grow in grain and grain products are influenced by the initial moisture, temperature, and oxygen concentration, by the direction and extent to which these and other factors (such as pH, nutrient supply, and antibiotic substances) change as molds and other microorganisms grow, and by the inherent growth rates of each mold. More kinds would be expected to grow as moisture and temperature become favorable, but the actual number falls short of expectations because of the effect of other factors. Except for moisture, the influence of other factors on the kinds of molds growing in grain and grain products is little known.

As shown in Table XXII, molds (including several yeastlike fungi) growing in stored grain and grain products are chiefly members of the genera *Aspergillus* and *Penicillium*, and of the orders Mucorales and Moniliales. Morphological details of some of the molds commonly found on or in stored grain are shown in Figure 6. Many of the Moniliales are parasites, semiparasites, or saprophytes of high water requirement, having minor significance in the deterioration of grain and grain products in storage. Parasites or semiparasites such as *Cephalosporium acremonium*, *Nigrospora oryzae*, *Gibberella zeae*, and *Diplodia zeae* do

Fig. 6. A close view of spore-bearing structures, spores, and mycelium of several fungus genera commonly found on or in stored grain: Aspergillus (A), Penicillium (B), Rhizopus (C), Alternaria (D), and Helminthosporium (E). (Courtesy of Department of Plant Pathology, University of Minnesota, through Mary A. Swaebly.)

not grow on shelled corn of lower than 21% moisture, although some strains of *Fusarium moniliforme* may grow on corn with 18.4% moisture (209). All these molds may grow slightly or extensively on freshly harvested ear corn of 32% moisture when it is dried at moderate or slow rates (210). Helminthosporium and Alternaria species, which are frequently found on wheat and other cereal grains, develop slightly in feed stuffs near 100% relative water-vapor pressure (364) and in wheat with more than 25% moisture (27?).

Snow (364) studied microscopically the molds growing at fixed moisture levels in various feed stuffs held at 60° to 70°F. He noted the growth of certain members of the Aspergillus glaucus group and of *Aspergillus candidus* at relative humidities from 100% to as low as 65 or 70%. Other members of the Aspergillus glaucus group, other Aspergilli, Penicillia, and Mucor species grew only at relative humidities above 70% (Table XXIII). At 100% relative humidity, members of the Mucorales developed rapidly within 2 to 3 days and were accom-

TABLE XXII

Fungi Recorded From Stored Cereal Grains and Grain Products

1. MUCORALES (86)

Absidia racemosus (350)
A. lichtheimi (350)
Syncephalastrum sp. (399)
S. racemosum (350)
Thamnidium elegans (160)
T. aurantiacum (160)

Mucor spp. (18, 52, 79, 160, 393)
M. racemosus (350)
M. spinosus (364)
M. ambiguus (160)
Rhizopus spp. (271)
R. nodosus (160)
R. nigricans (160, 256, 364, 377, 399, 442)
R. arrhizus (350)

2. ENDOMYCETALES

Endomyces fibuliger (160)

3. EUROTIALES

(A) Penicillium (398)
P. glaucum (406)

Monoverticillata group
(a) Stricta
P. spinulosum (364)
(b) Ramigena
P. cyaneum (350)

Asymmetrica group
(a) Velutina
P. chrysogenum (209, 350)
P. notatum (209)
P. oxalicum (209, 399)
P. puberulum (4)
P. viridicatum (256, 257)
P. westlingi (350)

(b) Brevi-compactum
P. brevi-compactum (18)
P. patris-mei (18)
P. stoloniferum (4)

(c) Fasciculata
P. crustaceum (160)
P. cyclopium (18, 209, 364)
P. expansum (18, 209, 248)
P. olivinoviride (256)
P. verrucosum (350)
P. viridicatum (209, 257, 278)
P. palitans (209, 350)

Biverticillata-symmetrica group
P. luteum (364, 399)
P. purpurogenum (399)
P. rugulosum (350, 364)

(B) Aspergillus (400)

A. clavatus group
A. clavatus

A. glaucus group (52, 78, 79, 160, 209, 248, 256, 271, 406)
A. amstelodami (350, 364)
A. chevalieri (350, 364)
A. echinulatus (364)
A. herbariorum (321)
A. penicilloides (364)
A. repens (350, 364, 399)
A. ruber (350, 364)

A. fumigatus group
A. fumigatus (52, 79, 160, 256, 350, 399, 406)

A. nidulans group
A. nidulans (160, 350)

A. versicolor group
A. sydowi (364)
A. versicolor (79, 209, 364)

A. terreus group
A. terreus (52, 350)

A. candidus group
A. albus (248)
A. candidus (78, 79, 160, 271, 350, 364, 377)

A. niger group
A. niger (52, 79, 160, 209, 271, 350, 364, 399, 404, 406)

TABLE XXII (Continued)

FUNGI RECORDED FROM STORED CEREAL GRAINS AND GRAIN PRODUCTS

3. EUROTIALES (continued)	(B) Aspergillus (continued)
(A) Penicillium (continued)	A. wentii group
Polyverticillata-symmetrica group	*A. wentii* (209)
Paecilomyces varioti (364)	A. tamarii group
Scopulariopsis sp. (321)	*A. tamarii* (79, 209, 399)
Citromyces Thomi (350)	A. flavus-oryzae group
Citromyces spp. (248, 399)	*A. effusus* (406)
Unidentified (52, 78, 79, 271, 377, 399, 404)	*A. flavus* (52, 79, 160, 209, 271, 350, 399, 404, 406)
	A. ochraceus group
	A. ochraceus (52, 79, 160, 209, 406)
	A. ostianus (377)
	Unidentified (18, 52, 248, 377, 404, 442)
	A. varians (406)
4. HYPOCREALES	
Gibberella (209)	
G. zeae (350)	
5. MONILIALES (86)	
Botrytis (18)	*O. verticillioides* (406)
Candida sp. (52)	Rhinotrichum (350)
C. pseudotropicalis (52)	Sporotrichum (364)
Cephalosporium (79, 209, 350)	Trichoderma (271, 350, 364)
Cephalothecium roseum (404)	*Verticillium cinnabarinum* (364)
Fusarium (52, 399)	Alternaria (52, 79, 399, 404)
F. moniliforme (79, 350)	*A. tenuis* (364)
F. roseum (404)	Cladosporium (18, 399)
Fusidium griseum (350)	Dematium (350)
Monilia candida (79)	Helminthosporium (79, 404)
Oospora (350)	*Hormodendrum cladosporioides* (406)
O. aegeritoides (406)	Nigrospora (79, 209, 271, 350)
6. SPHAEROPSIDALES (86)	
Diplodia (79, 209, 350)	
D. maydis (406)	

panied within a week by members of the Aspergillus glaucus group and Penicillium spp., within another week by *Aspergillus niger,* within the third week by *A. candidus,* and later by members of the Fungi Imperfecti, such as *Sporotrichum* sp. On shelled corn stored at 70°F., Koehler (209) observed growth of Aspergillus glaucus at a minimum moisture of 14.4%, *Aspergillus wentii* at 15.1%, *Penicillium* sp. at 16.3%, and *Aspergillus flavus* and *A. niger* at a minimum moisture content of 18.3%. These moisture levels corresponded to the minimum moisture requirements for growth of these fungi in pure culture on surface sterilized corn. On

TABLE XXIII

MINIMUM RELATIVE HUMIDITY BELOW WHICH DIFFERENT MOLD SPECIES WERE NOT ISOLATED FROM FEEDING STUFFS
(After Snow, 364)

Relative Humidity	Mold Species
%	
100	*Penicillium rugulosum* *Trichoderma* sp. *Rhizopus nigricans* *Verticillium cinnabarinum* *Alternaria tenuis*
90	*Aspergillus niger* *Penicillium luteum* *P. cyclopium* *Sporotrichum* sp. *Mucor spinosus*
85	*Aspergillus versicolor* *A. sydowi*
80	*Aspergillus chevalieri* *A. amstelodami*
75	*A. penicilloides* series *Paecilomyces varioti* *Penicillium spinulosum*
70	*Aspergillus ruber* *A. candidus*
67	*A. repens*
65	*A. echinulatus*

wheat stored at room temperature, Hurd (175) observed growth of only Aspergillus spp. at 70% relative water-vapor pressure and of Aspergillus and Penicillium species when the relative water-vapor pressure was 80% or more.

Milner, Christensen, and Geddes (272) used culture methods to study the growth of molds in wheat stored at different moisture levels for 20 days at 30°C. They found only Aspergillus glaucus at 15.4% moisture, mainly Aspergillus glaucus and smaller proportions of *Aspergillus flavus, A. candidus,* and *Penicillium* sp. at 16.8% moisture, and mainly *Aspergillus candidus* and smaller amounts of Aspergillus glaucus, *A. flavus, A. ochraceus,* and *Penicillium* sp. at 18.5% and 20.8% moisture. At 25.2%, 30.5%, and 38.6% moisture, *Aspergillus flavus* was most abundant and *Penicillium* sp. was least abundant, while Aspergillus glaucus was absent; *Aspergillus candidus* was present only at 25.2% moisture and *A. niger* was present only at 30.5% and 38.6% moisture.

After the same storage period, the mold flora of wheat carrying 12.3%, 13.6%, 13.8%, and 14.5% moisture consisted of Penicillia and Aspergilli, even though final mold counts and periodic determinations of respiration rates indicated no mold growth, except possibly in 14.5% moisture wheat.

Using a similar method for evaluating growth, Thom and LeFevre (399) found principally *Aspergillus repens*, which is a member of the Aspergillus glaucus group, in stored cornmeal with 13 to 15% moisture. This same fungus, *Aspergillus flavus, Penicillium* sp., *Citromyces* sp., *Fusarium* sp., *Aspergillus candidus, A. ochraceus, A. tamarii,* and *A. niger,* in order of decreasing abundance, were found in stored cornmeal with higher moistures. Also by this method, Bottomley, Christensen, and Geddes (53) evaluated the growth of molds in shelled corn stored for 12 days at 30°C. in bottles through which air of constant humidity was drawn. They found a simultaneous slight development of *Aspergillus flavus* and *Penicillium* sp. (with or without Aspergillus glaucus, *Mucor* sp., *Aspergillus candidus,* and *A. tamarii*) at 80% relative humidity; abundant growth of Aspergillus glaucus and less abundant growth of *Aspergillus flavus* and *Penicillium* sp. at 85% relative humidity; nearly equally abundant growth of Aspergillus glaucus, *Aspergillus candidus, A. flavus,* and Penicillium spp. (with or without a less abundant growth of *Aspergillus tamarii, Mucor* sp., and *Fusarium* sp.) at 95% relative humidity; and nearly equally abundant growth of *Aspergillus flavus* and *A. tamarii* (with or without a less abundant growth of *Penicillium* sp., *Mucor* sp., and *Fusarium* sp., and occasional traces of Aspergillus glaucus) at 100% relative humidity.

Growth of Penicillia and other fungi has been observed in wheat with 22.8% moisture when stored in open boxes for 3 months at —5°, 0°, 5°, 10°, and 20°C. Under the same conditions Aspergilli did not grow at 10°C. or at lower temperatures (216). *Aspergillus fumigatus, A. nidulans, Mucor heterosporus, M. dimorphosporus,* and species of Rhizopus, Aspergillus, and Penicillium have been reported to grow in moist wheat during artificial drying with air streams as hot as 100°C., and with grain temperatures as high as 50°C. (320). At temperatures below 25°C., Aspergillus glaucus was the first to grow on bread leavened with sour dough, *Rhizopus nigricans, Oospora variabilis,* and *Penicillium crustaceum* the first to grow on yeast-leavened bread, and *Oospora variabilis* was the first on sugar-containing hardtack (160). At 30° to 35°C., *Penicillium olivaceum* usually appeared first followed by *Oospora variabilis, Aspergillus fumigatus, A. niger, A. flavus,* and *A. nidulans,* and, after a week, by *A. candidus. Mucor pusillus* usually appeared in the interior of the loaf after a week at these temperatures.

In corn stored 12 days at different temperatures, moisture levels, and oxygen concentrations, Bottomley, Christensen, and Geddes (52), using culture plate methods, found growths of different kinds of fungi, depending more on temperature than on moisture or oxygen concentration. The principal fungi were *Mucor* sp. and/or *Penicillium* sp. at 45°C., *Aspergillus flavus* (at higher moistures), and Aspergillus glaucus (at lower moistures) at 35° and 40°C., *Aspergillus flavus* at 30°C.; and Aspergillus glaucus, *Aspergillus flavus,* and *Penicillium* sp. predominated at 25°C. The principal fungus at 25°C. was *Candida pseudotropicalis* when the oxygen concentration was 0.1% and the relative water-vapor pressure was 85 to 100%.

In shelled corn containing 13.5 to 14.0% moisture, stored over the winter period in Iowa in steel bins holding from 1,000 to 2,740 bushels, Semeniuk, Nagel, and Gilman (350) observed a stratification of different fungi near the upper surface of the bulk corn, which seemed to be related to differences in temperature and moisture. *Penicillium palitans,* whose minimum growth temperature was less than 0.5°C. and whose minimum moisture requirement was 82.5% relative water-vapor pressure, was frequently the only fungus matting the corn in the upper one-foot zone in these bins. *Aspergillus flavus,* whose minimum growth temperature was higher than 9°C. and whose minimum moisture requirement was 82.5% relative water-vapor pressure, was occasionally found as a yellowish-green band of varying width immediately below the layer of *Penicillium palitans.* Heat production was generally associated with development of these fungi. *Aspergillus candidus,* whose minimum growth temperature was higher than 9°C. and whose minimum moisture requirement was 72.5% relative water-vapor pressure, was occasionally abundant in drier corn at the outer edges of, or immediately below, the warm regions of *A. flavus.* Fungi of the Aspergillus glaucus group were frequently found in drier corn below, or at the edges of, the heating, mold-matted corn. In this group *A. amstelodami* was found to have a minimum growth temperature higher than 9°C. and a minimum moisture requirement of 72.5% relative water-vapor pressure. "Blue-eye" corn was also found occasionally on the outer edges of the mold-matted areas, but more frequently near the surface of the corn in bins where other molds were not evident. *Penicillium rugulosum, P. palitans,* and *P. chrysogenum* with minimum growth temperatures of less than 0.5°C. and minimum water requirements of 85.0 to 87.5% relative water-vapor pressure were isolated from "blue-eye" corn. In shelled corn stored through a winter, spring, and summer period, stratification of molds in the upper regions of similar bins frequently became obliterated by extensive growth of Mucor, Rhizopus, and Absidia species through most of the mold-matted area.

Strata of such fungi as Penicillium spp., *Aspergillus flavus, A. candidus,* and members of the Aspergillus glaucus group, and "blue-eye" corn, however, were noted in about the same relative positions as in corn stored over the winter period only. Strata of Rhinotrichum and Oospora species occasionally were noted in close association with strata of *Aspergillus flavus.*

The kinds of molds that grow or cease to grow in grain and grain products as microorganism activity continues under adiabatic or semi-adiabatic conditions of storage have not been investigated specifically. Presumably the kinds would change from xerophytes or mesophytes to hydrophytes, and from psychrophiles or mesophiles to thermophiles, depending on the moisture and temperature conditions at the start of microbial growth and thereafter. The kinds will depend also on microbial by-products, pH, oxygen, and nutrient supply. *Aspergillus fumigatus* (87, 132, 321), *A. flavus* (12, 132, 321), *A. niger* (12, 132), *A. candidus* (321), *A. herbariorum* var. *minor* (321), *Scopulariopsis* sp. (321), *Cunninghamella spinosa* (320), *Mucor heterosporus* (320), *Penicillium* sp. (320), Rhizopus, Penicillium, and Fusarium species (12), and a fungus resembling *Thermomyces lanuginosus* (26) have been isolated from or found growing in spontaneously heating grain and grain products, but their places in the changing mold flora have not been determined. Mead, Russell, and Ledingham (262) reported the successive appearance of Penicillium spp., Aspergillus spp., and thermophilic fungi in wheat with 24% moisture as the temperature rose spontaneously from 20° to 51°C. In heating plant materials, which carry nearly the same microflora as cereal grains, Miehe (268) and Noack (290) noted the appearance of *Oidium lactis* in moist hay at temperatures near 40°C. and thermophilic forms such as *Mucor pusillus, M. corymbifer, Aspergillus fumigatus, Thermoascus aeruginosus* (probably *Dactylomyces aeruginosus,* 86), *Thermoidium sulfureum* (= *Malbranchea sulfureum,* 86), and *Anixia spadicea* at temperatures of 50°C. Düggeli (103) observed the presence of oidiumlike fungi in hay that had heated to 50°C., while Waksman, Cordon, and Hulpoi (416) noted the presence of thermomyceslike and monilialike or oidiumlike groups in manure composts held at 50°C. The latter investigators (416) found that molds seldom grew in manure composts held at 65°C. and never at 75°C. Miehe (268) noted self sterilization of spontaneously heating hay when the temperature was maintained at 57.5° to 68.5°C. for 20 days.

Yeasts and Yeastlike Fungi. Little is known about the activity of yeasts and yeastlike fungi in stored grain and grain products. They survived on wheat dried in air streams of 90°C. when grain temperatures reached 48°C. (320), but in only one instance have they been reported as growing

in spontaneously heating wheat (32). As mentioned in the preceding section on mold growth, several yeastlike fungi have been observed to grow in stored grain and grain products. These are *Candida pseudotropicalis* (52), *Oospora variabilis* (32, 160), *Candida* sp. (52), *Oospora* sp. (350), *Rhinotrichum* sp. (350), and probably *Sporotrichum* sp. (364). Perhaps the sweet odors occasionally found in deteriorated grain are due to yeast growth.

Bacteria. Numbers of bacteria decrease during artificial drying of grain (108, 320) and during storage of grain and grain products when moisture is subminimum for their growth. Reductions in their abundance during dry-storage have been reported as follows: (a) 99% in barley stored 3 months in the laboratory (167); (b) 83 to 91% in patent, straight-run, and fourth break flours stored 10 weeks in the laboratory at 77% relative humidity (200); (c) 15 to 30% in patent, straight, and clear flours stored 20 weeks in the laboratory (144); (d) 64% in a Manitoba wheat flour of 14.6% moisture content and in an English wheat flour of 16.5% moisture content stored 10 weeks in the laboratory; and near 90% in these same flours raised to 18% moisture content and stored under the same conditions (18). Spore-forming bacteria *(Bacillus mesentericus)* also decreased in wheat when the moisture content was 18% or less (274). The bacterial flora did not change qualitatively as a result of these reductions. *Pseudomonas trifolii* was the principal bacterium on dry-stored as on freshly harvested wheat (320).

Bacteria require higher moisture levels for growth in grain and grain products than do xerophytic and most mesophytic molds, but the exact minimum moisture limits for their growth has not been determined. A limit of 90% relative water-vapor pressure has been reported for growth of *Micrococcus roseus* (66). Bacteria have variously been reported to grow in wheat of 17% moisture (403), 18.4% moisture (87% relative water-vapor pressure) (271), and 22.8% moisture (216). They are also said to require not less than 20% moisture in wheat (274) and a relative water-vapor pressure of 85% (274). They have been reported to grow in corn of 20% moisture (248); in cornmeal of 18 to 20% moisture (399); and in flour of 20% moisture (211) but not 18% moisture (18). Their growth contributes to spontaneous heating and to the formation of sick wheat. They also cause sour and putrid odors, ropy bread, and other types of deterioration when moisture supplies are adequate.

The total number of bacterial cells and the number of spores (mainly of *Bacillus mesentericus*) increased slightly within 20 days on wheat at 94% and 98% relative water-vapor pressure when the temperature was 20°C., and significantly at 85%, 90%, 94%, and 98% relative vapor pressures when the temperature was 37°C. (274). Within 50 days the total

number of bacterial cells and the number of spores had increased markedly at both temperatures and all moistures, the increases being greater at the higher temperature and the higher relative vapor pressures.

At 20°C. nonsporing bacteria increased slightly in moist wheat stored 15 days in rubber-stoppered bottles, while they increased greatly at 37°C. and decreased at 50°C. (274). Spore-forming bacteria increased most abundantly when the temperature was 50°C. At 45° to 55°C. spore-forming bacteria increased within 5 days on wheat carrying 20 and 23% moisture, while at 17° to 20°C. they required 3 months to increase on wheat with 23% moisture. This suggests that temperature and moisture interact on the growth of these bacteria in much the same way as they do on the growth of molds.

At lower temperatures, —5°, 0°, 5°, 10°, and 20°C., spore-forming bacteria did not increase within 3 months on wheat containing 22.8% moisture stored in open boxes, while micrococci increased and *Pseudomonas trifolii (Bacterium herbicola aureum)* decreased at 0°C. and the higher temperatures. At 25°C. micrococci replaced *Pseudomonas trifolii* as the principal bacteria on wheat with 16% and 18% moisture stored for 50 days (216).

During spontaneous heating, mesophilic bacteria increased rapidly in cracked corn as the temperature rose to 50°C. and declined as the temperature reached 55°C. or above (181). Thermophilic bacteria, which grow at 50°C., were not found until a temperature of 55°C. was reached. *Pseudomonas trifolii* increased in 28.2% moisture wheat as the temperature rose from 15° to about 24°C. and decreased rapidly as the temperature rose higher (217). Micrococci and Sarcinae increased rapidly as the temperatures increased from 24°C. to about 50°C. but decreased as the temperatures rose higher. Spore-forming bacteria (mainly *Bacillus mesentericus*) increased as the temperatures approached 50°C. and continued to increase to at least 64°C. (217, 320).

Of interest in this connection are the changes observed in the bacterial flora of hay during spontaneous heating. Miehe (268) noted *Bacterium coli* forma *foenicola* (resembling *Bacterium herbicola aureum*) was the principal bacterium when the temperature was 30°C.; *Bacillus calfactor* was abundant and *Bacillus subtilis* less abundant at 40°C.; while *Bacillus calfactor* (resembling Clostridia) was abundant and the principal bacterium at 50°C. Düggeli (103) noted a change from the normal flora of *Pseudomonas fluorescens (Bacterium fluorescens liquefaciens* and *B. fluorescens non-liquefaciens)* and *B. trifolii (Bacterium herbicola aureum)* to *Bacillus subtilis, B. calfactor,* micrococci, and unknown short rod bacteria as the temperature of spontaneously heating hay rose to 57°C.

In spontaneously fermenting dough prepared from flour and water (158, 168, 238), (a medium in which there is an excess of water) the facultatively anaerobic, gas-producing *Aerobacter cloacae* (syn. *Bacterium levans* Wolffin and *Bacterium coli albidoliquefaciens* Levy) and a Proteus species (*Bacterium coli luteoliquefaciens* Levy) developed abundantly at first and were soon followed and dominated by the anaerobic, acid-producing *Streptococcus lactis* (syn. *Bacterium lactis acidi* Leichmann) or *Lactobacillus plantarum* (syn. *Streptococcus plantarum* Orla-Jensen). *Bacterium megaterium, Bacillus subtilis* (syn. *B. vulgatus*), Sarcina spp., various unknown cocci, and motile and nonmotile short-rod bacteria developed to a lesser extent, while *Pseudomonas fluorescens* and an anaerobic, clostridiumlike bacterium developed slightly.

Similarly, in fermenting bran prepared from two parts water to one of dry bran by weight (433), bacteria increased rapidly to peak numbers within 1 day at 37°C. and 2 days at 24°C., and subsequently decreased. Gas- and acid-producing bacteria of the species *Aerobacter aerogenes* (*Bacterium acidi lactici* Hueppe) and of the genus Proteus (*Bacterium coli luteoliquefaciens* Levy) and occasionally *Pseudomonas trifolii (Bacterium herbicola aureum)* developed most extensively during the early stage of the fermentation. About the time the bacterial population was at its highest they were accompanied by nearly equal numbers of *Streptococcus lactis (Bacterium güntheri), Clostridium lentoputrescens* (*Bacillus putrificus coli* Bienstock), *Pseudomonas fluorescens,* and occasionally *Pseudomonas punctata* (*Bacterium punctatum* L. & N.). *Streptococcus lactis (Bacterium güntheri)* generally predominated immediately beyond the peak of greatest bacterial number at 24°C. and 37°C. At 24°C. *Pseudomonas putida (Bacterium putidum), Pseudomonas fluorescens, Aerobacter aerogenes (Bacterium acidi lactici),* and occasionally *Clostridium lentoputrescens (Bacillus putrificus)* were also abundant, while at 37°C. *Bacillus subtilis (Bacillus mesentericus), Aerobacter aerogenes (Bacterium acidi lactici),* and *Clostridium lentoputrescens (Bacillus putrificus)* were present in small numbers.

Henneberg (158) discusses the influence of temperature, pH, and nutrient availability on the development of different bacteria in grain and malt mashes, in ensilage preparation, and in enrichment cultures prepared by adding bran, crushed green malt, or wheat wash water to saccharified barley malt mash.

Actinomycetes. Little is known about actinomycete activity in grain and grain products. Thermophiles were observed to increase on moist wheat that was being dried by air streams at 100°C. and with grain temperatures of 50°C. (320). They have also been observed to increase in wheat with 26% and 28% moisture during spontaneous heating to tem-

peratures of 41°, 48°, and 51°C. (217, 321). *Actinomyces albus* has been observed frequently and *A. griseus* less frequently in heated grain (321). Morgenthaler (278) found wide variations in the abundance of actinomycetes on musty and nonmusty cereal grains.

Damage to Quality by Microflora

Microorganism activity lowers the viability, storage qualities, nutritive value, edibility, and industrial usefulness of grain and grain products.

Viability. Grain viability drops rapidly when microorganisms grow. It also drops, though slowly, when microorganisms presumably fail to grow in stored grain. Its decline under the latter conditions is believed to be due to protein degeneration within the embryo (90), but the primary and contributory causes have not been well established.

Storage Qualities. Grain and grain products previously damaged by microorganisms deteriorate faster during subsequent storage, exhibiting greater respiration (11) and heating rates (447). The heating rate of corn appears to be predictable from its moisture content and fat acidity (447).

Nutritive Value. The nutritive value of grain and grain products is lowered by microorganism activity (80, 276). Its reduction is proportional to qualitative and quantitative changes in carbohydrates, fats, and protein (1, 18, 52, 88, 117, 149, 248, 276, 284, 316, 337, 376, 378), and to toxic and other body substances elaborated by microorganisms. Except for vitamin content (47, 134, 285, 383, 389, 414), the nutritive value of mold tissue is low (134, 355, 357, 358, 375, 383), although that of certain yeasts and yeastlike fungi and bacteria is high (56, 127, 304, 375).

Edibility. The edibility of deteriorated grain and grain products depends on the appearance, odor, and taste of the materials, and the toxins, allergens, and pathogenic or pseudopathogenic microorganisms they contain. The syndrome varies with the kinds of microorganisms that cause the damage, so that "deteriorated," "spoiled," or "moldy" grain and grain products are usually not alike even when produced under seemingly identical conditions. Deteriorated grain and grain products are usually harmful or potentially harmful to humans and animals, and for that reason they are cautiously eaten or fed.

Poultry, which thrive on moldy grain (47, 283, 285, 302, 327), may inhale an abundance of spores of *Aspergillus fumigatus* and develop aspergillosis (65, 99, 145). Horses are more sensitive to moldy grain than lambs, and the latter are more sensitive than cows or pigs (281). The health of animals may become impaired as a result of inhaling mold spores or ingesting moldy grain feeds from which respiratory, nervous, and intestinal disturbances develop, along with internal mycoses fol-

lowing the effects of allergens or toxins, or both (111, 145, 159, 207). Deaths have been reported in horses as a result of eating moldy corn (342), moldy bread (61), and grain feeds infected with *Clostridium botulinum* (137); in pigs after eating spoiled corn (196) and blighted barley (80); and in cows and sheep after eating moldy bran (61). But perhaps sickness rather than death is the cause of the greatest losses, because animals refuse to eat or to continue to eat heavily molded grain (106, 207). Pigs vomit grains carrying excessive amounts of *Gibberella zeae* (80, 173), while man develops headaches, dizziness, exhaustion, and shivering from bread prepared from similarly affected grain (100, 441). However, in three winter and spring feeding experiments, beeves, pigs, and lambs readily ate molded soft corn (Fig. 7) of around 30% moisture content without ill effects, and by eating more soft corn they made the same gains at lower cost as compared with animals fed hard corn of lower moisture content (166). Pigs also have eaten badly rotted soft corn without ill effects (264, 298). It is evident that the designation "moldy" as used in these various contexts has different meanings. Bacteria may be expected to grow in soft corn and affect its edibility, but not in nearly dry corn. Molds and bacteria vary in their toxicities to animals (27, 61, 84, 368, 413), but not enough is known about this to explain the variable effects of moldy feeds on animals.

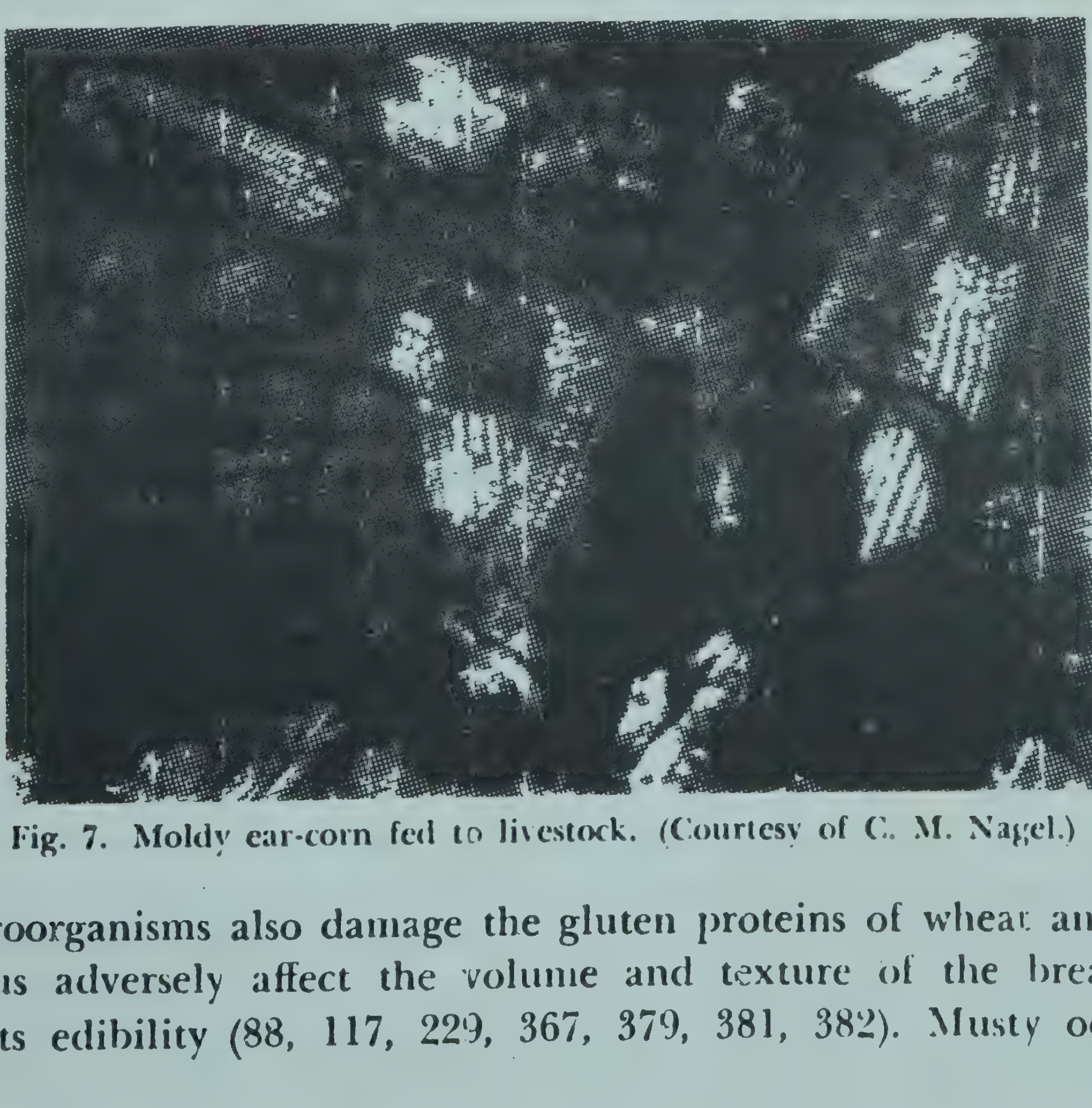

Fig. 7. Moldy ear-corn fed to livestock. (Courtesy of C. M. Nagel.)

Microorganisms also damage the gluten proteins of wheat and flour and thus adversely affect the volume and texture of the bread and hence its edibility (88, 117, 229, 367, 379, 381, 382). Musty odors in

grain or flour are transmitted to the bread if sufficiently strong, but not when they are weak (381, 442). Slight musty odors in grains can be removed or markedly reduced by sprinkling the grain with, or immersing it in, a solution of hydrogen peroxide (152, 324), by warming and aerating the grain or by exposing it to ozone (219), by pulverizing the grain and aerating the powder (402), by mixing the grain with charcoal (152, 324), or by treating it with sulfur dioxide (151, 152). Strong musty odors cannot be removed (219, 402).

Aside from the yeast which is added to the doughs, microorganisms appear to have no beneficial part in modern bread manufacture (201). During baking, the internal temperature of the loaf approaches or slightly exceeds 100°C. (121, 138, 377), while the moisture content of the finished loaf averages 36.9% (279). Rope-producing bacterial spores, which are universally present in flour, resist 100°C. for as long as 6 hours (138). Their development in bread within 36 to 48 hours to produce characteristic symptoms (19) is favored by high numbers of spores in the flour (6, 138), by a long fermentation period (199), by keeping the bread at temperatures of 77°F. and higher, and by a pH in the bread above 5 (243). Their development may be controlled by obtaining conditions that are opposite to these.

Mold development on bread arises from external contamination following baking (160, 280, 428). High relative humidity within and outside the wrapper (121, 359) and high temperatures (377) favor mold development, while strong acid conditions retard it (203, 204). Mold development on bread can be retarded by impregnation of the wrapper with calcium propionate (180) or succinates (48), or the addition of calcium propionate to the dough or to the crust (180). Exposure of the wrapped loaf to ultraviolet light (322), electronic radiation (16), or high-frequency heat waves (70) is claimed to destroy surface spores.

Industrial Usefulness. Moldy corn is unsuited to the wet-milling starch industry because of difficulties in separating the products and in obtaining good quality and yield of products (202). Slightly damaged wheat is suitable for dry-milling for flour or starch production, but more severe damage produces starch or flour with off-odors and modified properties (251). Internally infected barley is unsuitable for malt production because of uneven grain germination and inferior malt quality (309). Boruff, Claassen, and Sotier (50) drew attention to the need for control of the microorganisms in cereal grains used in distilleries. They pointed out that the Hiram-Walker 'Distilleries' acceptance standards set a maximum of 10 million bacteria per g. of grain as determined on ground samples. Considerable variation was noted in the bacterial content of corn as received during different months of the year.

Control of Microflora in Grain and Grain Products

Moisture, temperature, aeration, pH, and toxic chemicals are keys to the control of microorganism activity. To have effective control, all microorganisms must be affected.

Moisture. Adjustment of moisture is the practical method for arresting the activity of microorganisms in the storage of cereal grains and their products. Moisture content equivalent to 65% relative humidity is borderline for long-time storage, while higher moisture contents, equivalent to 70 and 75% relative humidity, may be allowed for short-time storage at low temperatures and for protein-poor substrates. Moisture limits for safe storage will vary with the character of the storage facilities, the weather, and the expected period of storage.

Temperature. Lowering the temperature of the product below the optimum for most fungi (23° to 30°C.) reduces the activity of these organisms and also raises the minimum relative humidity at which growth is supported. Schwartz and Schmid (344) noted that lowering the temperature from 4°C. to 1°C. had the same effect on the growth of bacteria on meat as lowering the humidity by 5%, while lowering the temperature from 6°C. to 3°C. had the same effect on fungi (343) as lowering relative humidity by 5 to 20%. A similar effect of temperature on the deterioration of wheat (381) and flour (20) is suggested.

Aeration. Grain products containing insufficient moisture to support bacterial growth may be stored effectively under strictly anaerobic conditions (37) because mold growth would be inhibited under these conditions. Restricted aeration may retard but not prevent mold activity. Increasing carbon dioxide concentrations in the atmosphere to high values is ineffective for control of microorganism growth as high concentrations are tolerated (147, 335, 435).

Hydrogen-ion Concentration. The lower pH limit for the growth of most bacteria is 4.0, while for most fungi the limit is 2.0 to 3.0 (147, 360). The optimum pH for bacterial growth is 6.0 to 7.5 and for fungal growth between 4.0 and 7.5. Vinegar and calcium acid phosphate at one time were commonly added to bread dough during summer months to inhibit development of rope-producing bacteria. Sodium diacetate, and sodium or calcium propionate, are now widely used to control molds and rope in bread and other bakery products.

Toxic Chemicals. Chemical control of microorganism activity has not found a place in grain storage although it has in the preservation of bread and in the sterilization of flour. Many chemicals have been tried without success (218, 273), but the search is only beginning (92, 226, 258).

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CHAPTER IV

Respiration and Heating

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The importance of cereal grains in the growth of civilization partly depends upon their excellent keeping qualities when stored in a relatively dry state. However, under unfavorable harvesting and storage conditions, the moisture content of the grain may be sufficiently high to permit heating and other types of damage such as discoloration, development of musty odors, loss of viability, increase in fat acidity, and deterioration in nutritive qualities. The value of the grain for both agriculture and industry is reduced according to the extent of these changes and, in extreme cases, the grain may become unfit for food purposes.

No progress was made in understanding the nature of these phenomena until many years after the epoch-making discoveries of oxygen by Priestley in 1774 and of plant respiration by de Saussure in 1797. Respiration, which involves the release of energy through the biochemical oxidation of carbohydrates and other organic nutrients, is common to all living organisms. Accordingly, since stored grain is living material, many early workers believed that its respiration was primarily responsible for heat production. When respiration proceeds rapidly enough to produce heat more quickly than it can be dissipated, the temperature of the grain rises and heat damage may occur.

Microorganisms are always present on the surfaces and within the seed coats of grain. Several early investigators observed that the heating of damp grain and other organic substances, such as hay and straw, is usually accompanied by the growth of molds, but the part molds play in the heating and spoilage of stored grain has been very difficult to evaluate. Some investigators have ignored the microorganisms entirely, while others have believed that molds are primarily responsible for the heating phenomena. It is now quite generally recognized that the heat produced in stored damp grain is due both to the respiration of the grain itself and to the growth of fungi. If the grain is infested with

insects, they also contribute to the total respiration and heat production. Although there is some lack of agreement concerning the relative importance of respiration by the grain and by the fungi that are invariably present, the majority of workers now favor the view that molds cause the sharp increase in respiration that occurs when the moisture content of the grain exceeds a certain critical range and that their respiratory activity predominates under such conditions.

While the combined respiratory activities of the grain, molds, and insects are doubtless responsible for the primary heating of damp stored grain, these activities come to an end at about 55°C. and cannot account for higher temperatures. Some investigators have reported that chemical auto-oxidation may take place simultaneously with, or independently of, biological activity and is responsible for the heating of hay and other organic products, such as coal, to ignition temperatures.

A study of the respiratory rate of grain and of the various factors which affect it provides a fundamental approach to certain problems involved in grain storage. Observations made during the commercial handling and storage of grain are costly and are of limited value in determining the relative significance of the different variables involved. In laboratory experiments, the quantity of heat produced is so small and difficult to measure that the production of carbon dioxide under precisely controlled conditions has been the most commonly used criterion of the influence of different variables on the storage behavior of grain. Recently, however, methods have been developed for following the heating of small lots of grain under adiabatic conditions.

In this chapter, the main features of aerobic and anaerobic respiration are briefly presented. An account is next given of the different methods that have been employed for measuring grain respiration. The various factors which influence the respiration of grains, such as moisture content, temperature, and aeration, are then discussed. The contribution of microorganisms and insects to the total respiration is emphasized, and the chemical changes associated with high respiration rates are outlined. Factors which affect seed viability are considered, especially those which appear to be related to the production of germ-damaged or so-called "sick" wheat. The literature dealing with laboratory studies of the heating of various grains, with particular reference to recent work under essentially adiabatic conditions, is reviewed. Finally, the interpretation and significance of these laboratory studies are discussed in relation to the heating of grain in bulk storage.

The Respiratory Process

Aerobic and Anaerobic Respiration. Respiratory processes occur in

every living cell and furnish the energy required by the protoplasm to carry on its vital metabolic functions. Under aerobic conditions, oxygen is absorbed and organic compounds, particularly carbohydrates and fats, are oxidized with the formation of carbon dioxide and water as end products. Oxidation of these substances also occurs in living cells without the use of molecular oxygen. This anaerobic respiration is involved in the fermentations carried out by many microorganisms to produce such end products as carbon dioxide, ethyl alcohol, and formic, acetic, propionic, and oxalic acids.

The complete combustion of a typical carbohydrate and fat is represented by the following equations:

D-glucose:

$C_6H_{12}O_6$	+	$6O_2$	→	$6CO_2$	+	$6H_2O$	+	677.2 Cal.
180 g.		134.4 l.		134.4 l.		108 g.		
1.0 g.		0.747 l.		0.747 l.		0.60 g.		3.76 Cal.

1.0 liter of oxygen consumed = 5.04 Cal.
1.0 liter of carbon dioxide produced = 5.04 Cal.

Tripalmitin:

$(C_{15}H_{31}COO)_3C_3H_5$	+	$72\frac{1}{2}O_2$	→	$51CO_2$	+	$49H_2O$	+	7616.7 Cal.
806.8 g.		1624 l.		1142.4 l.		883 g.		
1.0 g.		2.88 l.		1.42 l.		1.09 g.		944 Cal.

1.0 liter of oxygen consumed = 4.69 Cal.
1.0 liter of carbon dioxide produced = 6.67 Cal.

The quantitative relations illustrated by these equations reveal that the heat equivalents of the oxygen consumed and carbon dioxide produced vary with the type of substance which is oxidized.

In anaerobic respiration the end products are carbon dioxide and a number of relatively simple organic compounds. The cellular constituents undergo an internal oxidation and reduction, and the quantity of energy released per unit of substrate consumed is much less than in the aerobic process. This is shown by the following equations summarizing three types of fermentation of a hexose sugar by certain microorganisms:

$$C_6H_{12}O_6 \rightarrow \underset{\text{lactic acid}}{2CH_3CHOHCOOH} + 22.5 \text{ Cal.}$$

$$C_6H_{12}O_6 \rightarrow \underset{\text{ethyl alcohol}}{2C_2H_5OH} + 2CO_2 + 22.0 \text{ Cal.}$$

$$C_6H_{12}O_6 \rightarrow \underset{\text{acetic acid}}{3CH_3COOH} + 15.0 \text{ Cal.}$$

In much of the earlier literature, the respiration of stored seeds has been regarded as involving, principally, the complete oxidation of car-

bohydrates to carbon dioxide and water (16). This concept is an oversimplification of the complex phenomena which comprise cellular metabolism.

Aerobic and anaerobic respiration follow a common pathway and involve the participation of complex but closely integrated enzyme systems which utilize various metabolites, intermediate in their state of oxidation, between the primary substrates and the end products. In the normal respiration of plants and animals, the initial decomposition of the substrate is accomplished without the intervention of oxygen, but the resulting end products of this anaerobic phase are oxidized aerobically, mainly to carbon dioxide and water. Most organisms require free oxygen to function normally and can only live for a short time by anaerobic respiration. This may be due to the establishment of an equilibrium through the accumulation of end products, or to the toxic effects of end products on the protoplasm.

A detailed consideration of the biochemical mechanisms involved in respiration is beyond the scope of this chapter, and the reader desiring more specific information should consult a recent review (62, 154).

Respiratory Quotient. The ratio of the moles (or volumes) of carbon dioxide produced to the moles of oxygen consumed during respiration is called the respiratory quotient or R.Q. In calculating the respiratory quotient a number of corrections must be applied to the experimental data for oxygen consumption and carbon dioxide production. These include reduction of the gas volumes to standard temperature and pressure, and correction for water vapor pressure and for changes which occur in the concentration of nitrogen during gas exchange (24). This quotient is also dependent, in part, upon the type of compound being oxidized. Thus, if carbohydrates are utilized in normal aerobic respiration, the equation for the complete combustion of D-glucose in the foregoing section shows that the R.Q. will be unity since the volumes of carbon dioxide produced and of oxygen consumed are equal. On the other hand, the R.Q. for the complete oxidation of tripalmitin is 51/72.5 or 0.70. The caloric equivalents of oxygen corresponding to various respiratory quotients can be calculated from the average energy equivalents for the oxidation of carbohydrates (R.Q. = 1.0) and of fats (R.Q. = 0.7). These equivalents may then be utilized to compute the energy corresponding to a given oxygen consumption. This is the principle of indirect calorimetry.

In plant metabolism, the respiratory quotient must be interpreted with considerable caution since it is influenced by a number of factors other than the type of material consumed. When fats are converted to carbohydrates prior to their oxidation, some oxygen is consumed in this

transformation which is not reflected in the quantity of carbon dioxide evolved when the carbohydrate is oxidized. This seems to explain the low R.Q. for plant tissues in which the food reserves are stored as fats. Conversely, during the maturation of oil seeds, the R.Q. exceeds 1.0 since carbohydrates are being transformed to fats, and the oxygen which is set free is directly utilized in respiration, thereby decreasing the amount which must be absorbed from the atmosphere.

In respiratory studies of dormant apple seeds, Harrington (67) observed that the respiratory quotient increased with an increase in temperature which he attributed to a deficiency either of readily oxidizable substrate or of oxygen within the respiring tissues. He emphasized that neither oxygen consumption nor carbon dioxide evolution can serve as an accurate index of respiration as "both depend on external and internal conditions which affect the two differently, so that neither alone gives a complete picture, much less a satisfactory understanding of respiratory exchanges." In view of this comment, it is unfortunate that many investigators have used the carbon dioxide output as the sole measure of the respiration of cereal grains.

Despite the number of factors which may influence the respiratory quotients, they are useful as indices of the relative extent of aerobic and anaerobic metabolism occurring in grain supplied with various oxygen levels at controlled temperatures.

Measurement of Respiration

Two general methods have been employed in measuring the respiration of dormant seeds. In the one, the seeds are kept in a closed container for a sufficient length of time for a measurable change to occur in the interseed atmosphere. The quantity of carbon dioxide in the container is then usually determined, although a few workers have also made analyses for oxygen content. In the other procedure, the seeds are subjected to intermittent or continuous aeration, and the air which is withdrawn is analyzed for its carbon dioxide content and sometimes also for its oxygen content. Microtechnics for respiration measurements on samples as small as a single seed have become increasingly popular in recent years.

In the majority of respiration studies at moistures within the range of those which may be encountered in bulk storage of grain, simultaneous measurements of the oxygen and carbon dioxide content of the interseed air have not been made. Most workers have assumed that carbohydrates are the principal material oxidized.

Closed Systems. The respiration of grain has been most frequently measured by procedures in which the interseed air supply is not re-

newed during the course of the trial. The apparatus used by Bailey and his associates (13, 15, 16, 17) in their well-known studies of grain respiration is illustrated in Figure 1. A similar method has been employed by Coleman and co-workers (45), Larmour *et al.* (93), and Ramstad and Geddes (134).

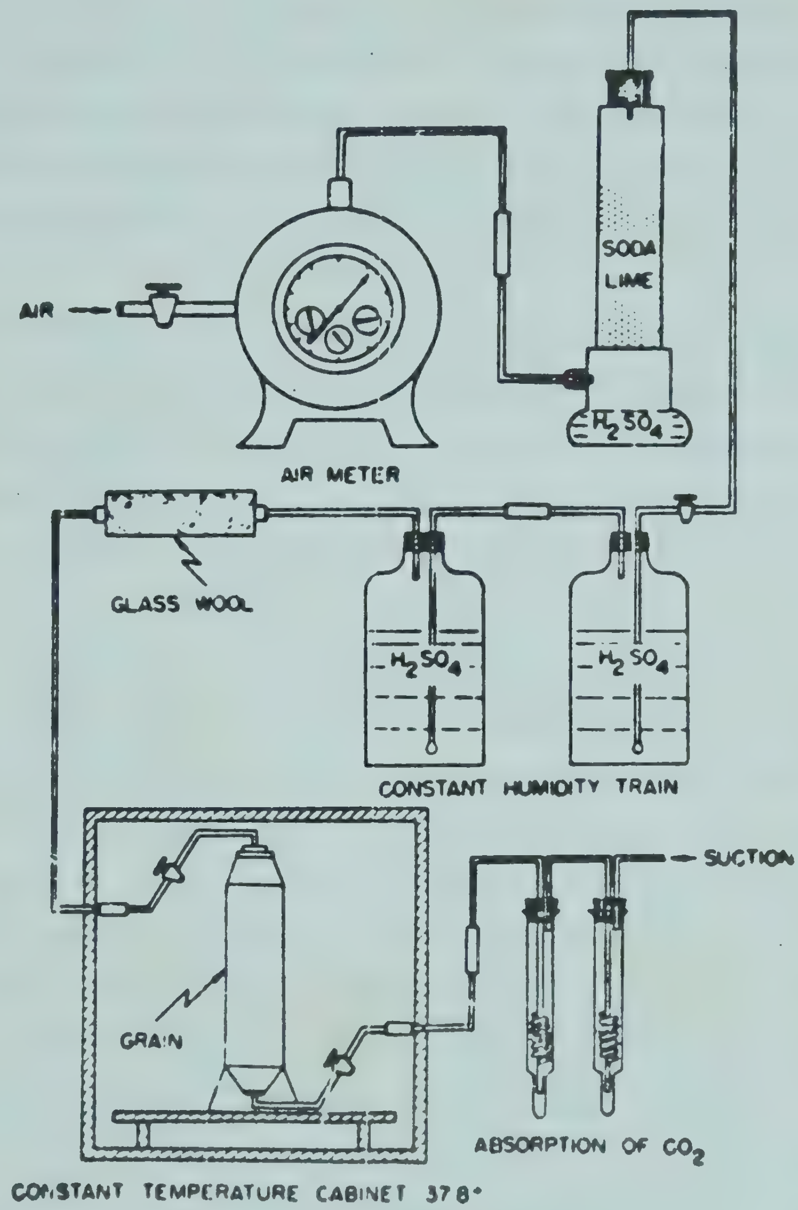

Fig. 1. Diagram of apparatus used in determining the rate of respiration of grains (from Bailey, 15).

Weighed quantities of grain (100–300 g.) of known moisture content are incubated for a fixed period of time (1 to 4 days) in a closed container at constant temperature. Bailey and his associates commonly conducted their trials at 37.8°C. (100°F.) since this is about the maximum temperature at which grain is placed in storage. At the end of the trial, sufficient carbon dioxide-free air is drawn through the grain to replace completely all the air in the system at least four times. The incoming air, after removal of carbon dioxide, is passed through a series of bottles containing sulfuric acid of the specific gravity required to bring the air to a relative humidity in equilibrium with the moisture content of the grain. The accumulated carbon dioxide is collected

in standard barium hydroxide solution contained in spiral absorbers, and the residual alkali back-titrated with hydrochloric acid, which must be weaker than 0.07 *N* (103), using thymolphthalein as indicator. The respiratory rate is expressed in terms of milligrams of carbon dioxide respired per 100 g. of dry matter per 24 hours.

In their studies of cottonseed respiration, Altschul and co-workers (5) stored cottonseeds in closed containers which allowed the respired carbon dioxide to accumulate. Measurements of the carbon dioxide and oxygen in the containers after intervals of storage were carried out with a manometric gas analyzer using suitable absorption media for removing the gases.

Denny (52) has recently described a simple method for investigating the respiratory exchange of multiple samples of damp grain. Mason jars are used as respirometers in which the seeds are placed above standard sodium hydroxide to absorb the carbon dioxide produced. The samples are connected in series with glass and rubber tubing through which a slow stream of oxygen is forced.

It has long been recognized that grain respiration is depressed by the accumulation of carbon dioxide in the interseed air (16). Larmour *et al.* (93) showed that increased air space in the respirometer, as well as more frequent aspiration, resulted in greater carbon dioxide production in samples of high respiratory activity. To reduce the possibility of inhibition of respiration by carbon dioxide accumulation, Ramstad and Geddes (134) adjusted the sample weights, and hence the free air space, in the respirometers so that the carbon dioxide production did not exceed an arbitrary maximum value. Other studies (112, 115) indicate that interseed atmospheres containing 12% or more of carbon dioxide depressed the respiratory rate of soybeans and wheat. Accordingly, it is advisable to keep the concentration well below this figure.

It seems probable that the static technic, involving the measurement of carbon dioxide production after a fixed period of 2 to 4 days, has frequently failed to reveal the maximum respiratory potential. In high-moisture samples the danger of respiratory depression is greater because of increased respiration.

The practice of allowing the carbon dioxide to accumulate for several days and averaging the results to yield a daily respiration rate obscures valuable information. As will be shown later, the respiratory rate increases with time under storage conditions which permit mold growth. Experimental data obtained at frequent time intervals provide more useful clues to the factors contributing to the respiration.

The widespread use of the static method was doubtless due in part to its simplicity and also to the assumption that the experimental con-

ditions were analogous to those which exist in bulk storage. However, it has been shown by Howe (74), Oxley (126), and Milner and Geddes (114) that air movements occur in heating grain in bulk which tend to prevent inhibitory concentrations of carbon dioxide in localized areas.

Aerated Systems. To avoid accumulation of carbon dioxide, Larmour *et al.* (95) ventilated the grain for short intervals each day. They also obtained daily values for carbon dioxide production during longer trials, and showed that respiration rates changed with time.

More precisely controlled conditions were obtained by Milner and Geddes (115) who devised a multiple respirometer in which grain held at constant temperature was aerated continuously at controlled rates which could be altered as desired. A diagrammatic sketch of the apparatus appears in Figure 2. Aeration is controlled by the slow displace-

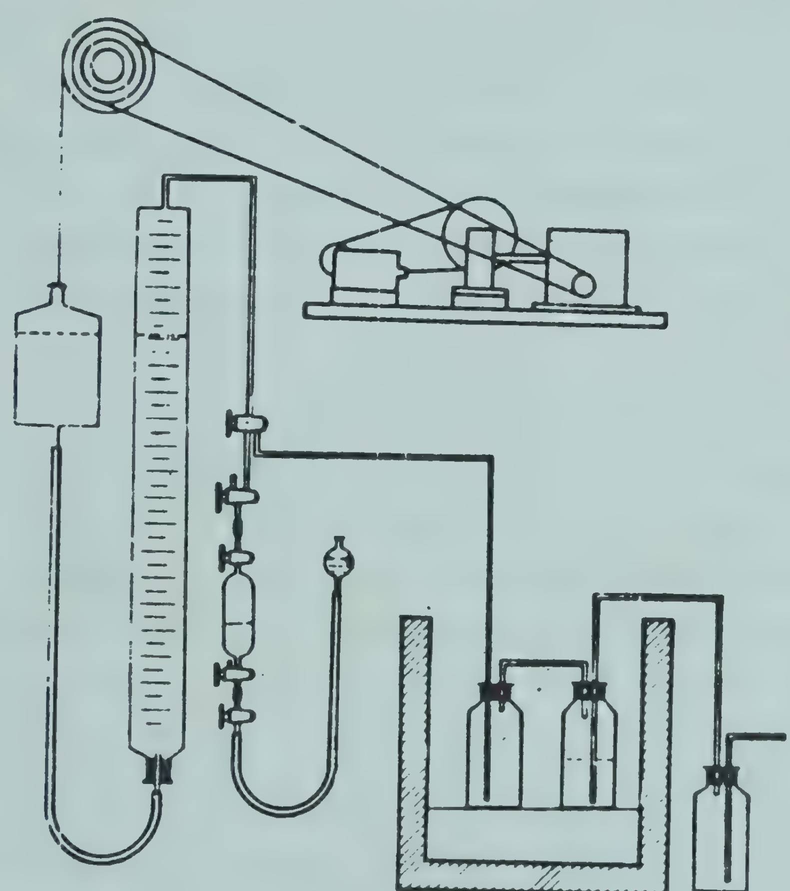

Fig. 2. Diagram of apparatus used to determine the respiratory rate of seeds at constant temperature (from Milner and Geddes, 115).

ment of calcium chloride solution (sp. gr. 1.40, in which carbon dioxide is only very slightly soluble) in graduated spirometers due to lowering the leveling bulbs suspended from pulleys on a slowly rotating line-shaft. Carbon dioxide-free air, suitably humidified, is thus drawn into the spirometer through the grain container, which is maintained at constant temperature in a controlled water bath. The effluent air in the spirometer is measured at 24-hour intervals, and a sample is analyzed for carbon dioxide and oxygen with a Haldane-Henderson gas analyzer by the technic outlined by Peters and Van Slyke (131). Data are thus obtained for the oxygen and carbon dioxide content of the

effluent air, the respiratory quotient (after applying a nitrogen correction as outlined by Best and Taylor, 24), and the total carbon dioxide production. The most accurate comparisons of the respiratory activities of different samples may be made when the daily rates approach a maximum value; under these conditions the standard error of a single determination was found to be 5 to 6%.

An apparatus operating on a similar principle has been used by Schricker (139) in a study of flaxseed respiration. Aeration was accomplished with mercury-operated pumps, and samples of the effluent air were taken by impaling membrane-stoppered vials upon blood-taking needles in the respiration train.

Microtechnics. The majority of workers interested in the bulk storage characteristics of grain have preferred to study large samples rather than to study one or several seeds by microtechnics. Large samples permit greater accuracy in measuring the extremely low respiration of dry seeds, and also decrease sampling errors. The presence on and within individual grains of varying numbers and kinds of molds (111, 118, 126), which respire actively under favorable conditions, renders data for one or a few seeds of doubtful value as an index of the behavior of the seed in bulk.

Stiles and Leach (153) originated a novel micro apparatus, known as a katharometer, for studying seed respiration. In the original model, only the oxygen consumption was measured by following the change in electrical conductivity of heated wires in the atmosphere of the respiration vessel. Conductivity has been shown to be affected by the extent of heat radiation from the wire which varies with the oxygen concentration of the atmosphere. A later modification of the apparatus (97) provided for determination of carbon dioxide by measuring the conductivity of standard alkali solutions used to absorb this gas. The Warburg-Barcroft manometric apparatus has also been used in respiration studies with wheat (38, 142) and rice (159).

Technics for Grain in Bins. The various forms of apparatus and technic just described have yielded valuable information on the respiration of grain under controlled laboratory conditions. The methods are not suitable for use in commercial grain practice as an aid in storage supervision. Accordingly, Oxley (124) devised a simplified carbon dioxide analyzer to determine the respiratory increases in dry grain which are indicative of insect proliferation. Milner and Geddes (114) also described a simple technic for the collection of interseed atmospheres for analysis. A hand-operated piston pump is used to create suction in a train comprising a pipe (3/8-in. diameter) inserted in the grain, gas sample tube, and a liquid-displacement volume-measuring device. Before the gas sam-

ple is taken, an amount of air equivalent to three times the calculated volume of the system is withdrawn. Since respiration is a highly sensitive index of biological activity, the perfection of a reliable method for obtaining interseed carbon dioxide values might prove to be a valuable aid in the supervision of stored grain.

Respiration of Dormant Grain

The early work on seed respiration, which has been reviewed by Miller (107), was concerned largely with seeds at moisture contents conducive to germination. However, in the past 30 years an increasing number of investigators have interested themselves in the respiration and associated changes which occur in grains at the considerably lower moisture levels which are encountered during harvesting and storage.

The total respiration of a particular lot of grain may arise from three sources, namely, the metabolism of viable grain, of microorganisms, and of insects. Insect infestation is frequently of minor significance, and the relative contribution of the grain and microorganisms depends upon a number of factors such as the kind of grain, its physical condition, moisture content, and chemical composition, and the temperature, aeration, and duration of storage. The many factors influencing respiration, and the complexity of their interactions, make systematic discussion difficult. In the following subsections, the general features of grain respiration are considered first; the principal contributory factors—moisture, temperature, aeration, and prior history—are then discussed in detail.

General Features of Grain Respiration. In dry grains, unless insect

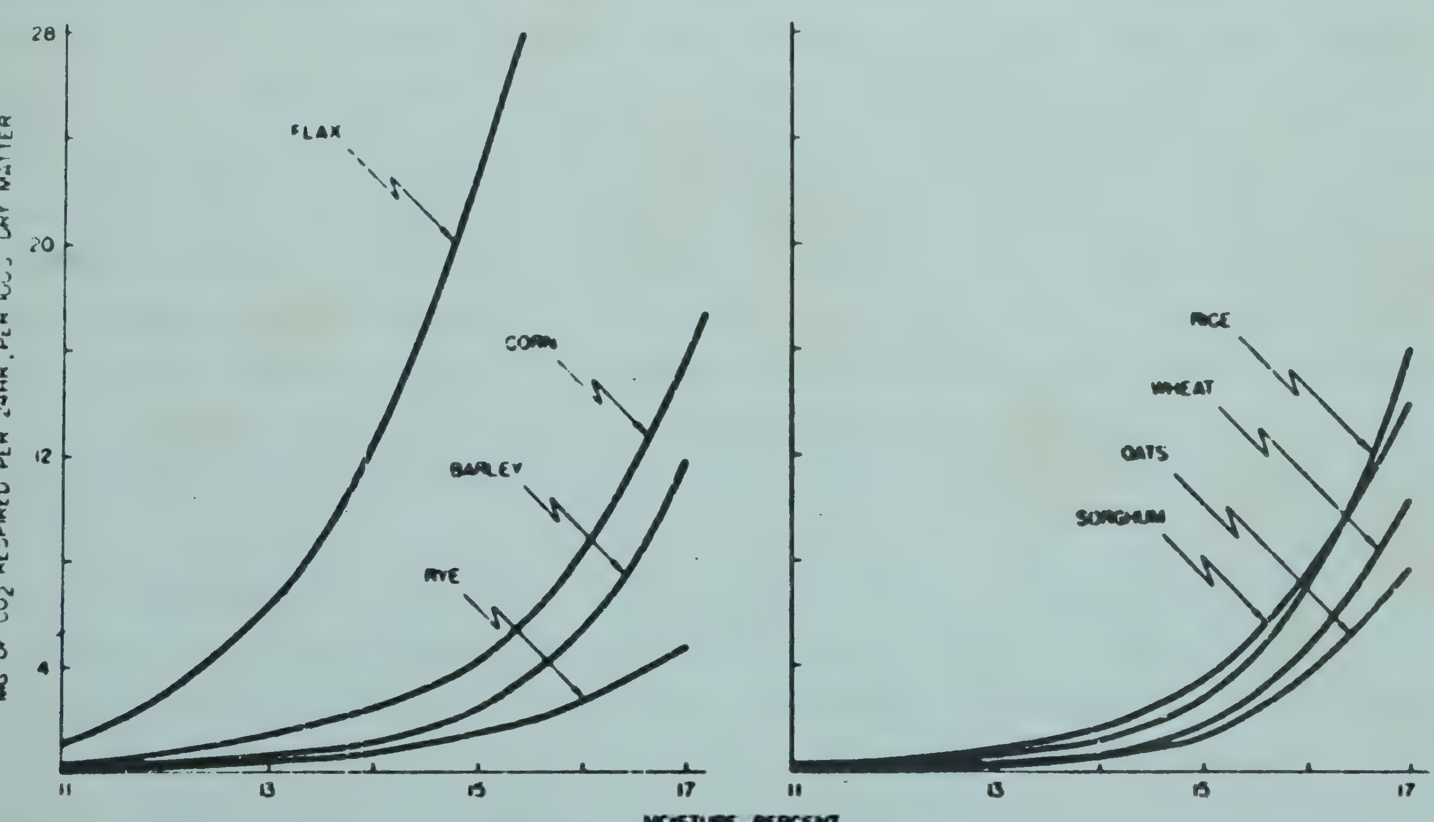

Fig. 3. Comparative respiration of various grains and flaxseed (from Bailey, 15).

infestation is present, the respiratory rate is very low. As moisture content increases, respiration of insect-free grain increases gradually until a certain critical moisture range is reached; above this range, the respiratory rate accelerates rapidly and the grain tends to heat. This outstanding feature of grain respiration is well illustrated in Figure 3, which summarizes work by Bailey and his associates (15, 16) aimed at establishing rational moisture limits for the various grades of grain in the U.S. grain standards.

Their respiratory trials were conducted in a closed system for a fixed time interval. Although all grains gave curves of the same general shape, the different species exhibited somewhat different critical moisture values. Thus, wheat appeared to have a critical value of about 14.6%, corn about 14.2%, and barley about 14.5%. Flaxseed was conspicuous with a low critical moisture value, somewhat under 11.0%, and a much higher respiratory rate than the cereal grains. The moisture contents at which a marked rise in the respiratory rates occurred in these laboratory studies are near those at which heating and spoiling of these grains begin in storage.

The difference between the critical moisture contents for flaxseed and for the cereal grains led Bailey (15) to suggest that, since the 40% (approx.) of oil in flaxseed is nonhygroscopic, only 60% of the dry matter retains water. A moisture content of 10% for the entire flaxseed implies a moisture content of about 16.5% in the hydrophilic portion; on the latter basis, the critical moisture value for flaxseed agrees approximately with those for cereal grains. This explanation, however, fails to hold for soybeans, which contain as much as 20% oil and yet resemble the cereal grains in having a critical moisture value of about 14%.

Several investigators have attempted to clarify the influence of composition on hygroscopicity. As has been mentioned, Bailey (15) suggested that the equilibrium moisture content of seeds is related to the amount of nonhygroscopic constituents. Ramstad and Geddes (134) believed that ash content may also influence the colloidal water-binding due to the intervention of inorganic ions. Larmour *et al.* (94), on the other hand, discount the influence of ash content as well as of percentage composition on hygroscopicity, and stress the importance of the kinds of hygroscopic components.

A thorough study of these relationships was made by Snow, Crichton, and Wright (150) who separated seeds into the starch, protein, and fiber components in order to ascertain the hygroscopicity of each fraction. Fiber exerted a depressing effect on water absorption, as did inert fats and nonhygroscopic ash constituents. They found that the ratio of soluble carbohydrate to protein was most closely related to percentage water

absorption and to the shape of the absorption curve.

Several early investigators observed fungi in spoiled or heating grain, and evidence recently accumulated indicates that the sharp increase in respiration that occurs above a critical moisture level is due to the growth of saprophytic molds. These molds are invariably present on the grain and underneath the seed coat (38, 60, 93, 98, 115, 116, 117, 121, 139, 140, 141). Several investigators have shown that a relative humidity of 75% is about a minimum for the germination of mold spores at ordinary temperatures. It is now quite generally agreed that the so-called critical moisture level for any individual species is the percentage moisture at which the seed is in equilibrium with an atmospheric relative humidity of about 75%.

Respiration trials in which the grain has been continuously aerated, and in which oxygen and carbon dioxide have been determined at regular intervals, have provided strong support for the view that the marked acceleration in respiratory rate above certain moisture levels is due to the growth of molds. In experiments with soybeans and wheat held at a constant temperature, Milner *et al.* (112, 116) obtained very low and virtually constant respiratory rates over extended time intervals when the moisture contents of the grains were below 14%.* Small increases in moisture content above this value were accompanied by respiratory increases over a period of several days, after which equilibrium conditions were approached. These characteristics are illustrated by the data for wheat in Table I.

The respiration-time curves for high moisture grain are similar in form to a microbiological population growth curve. When such grain respired under nitrogen, or in the presence of fungistatic agents that have little or no effect on germination, the respiratory rate remained almost constant from day to day (109, 113, 115). The effect of various concentrations of sulfanilamide on the respiratory behavior of wheat containing 20% moisture is shown in Figure 4. The respiratory rate of the control sample increased from 33 mg. of carbon dioxide (per 100 g. dry matter per day) on the first day of the trial to over 400 mg. on the

* In respiration trials, the normal rate of respiration may not be established for a few days; for it has been demonstrated that the seeds of several plant species release carbon dioxide when wetted or when their temperature is raised. This phenomenon has been noted for peas (56), flaxseed (139), and soybeans (116), and may also occur with other grains. The decline following the initial carbon dioxide output ceases in 24 to 48 hours; the normal respiration then ensues, whether it be the low values due to the seed itself or the increasing respiratory rates, after a latent period, indicative of the growth of fungi. That the early carbon dioxide release is probably not due to a high initial rate of respiration seems to be indicated by the fact that high respiratory quotients in the range of 1.5 to 2.0 appear during this process in soybeans and fall to a value of approximately 0.65 when the rate of respiration declines to a steady value (116). It thus appears that the phenomenon is due to the release of carbon dioxide which has been bound in the dry tissues.

A similar abrupt evolution of carbon dioxide has been noted when dormant soybeans and wheat are subjected to thermal killing such as occurs in spontaneous heating (112, 117). Values for the respiratory quotient in the range of 2.0 have been observed to accompany this peak of carbon dioxide release which occurs in the temperature range of 40° to 50°C.; thus the carbon dioxide is apparently released without a corresponding uptake of oxygen.

TABLE 1

RELATIONSHIP OF MOISTURE CONTENT TO RESPIRATORY RATE, MOLD GROWTH, VIABILITY, AND CHANGES IN FAT ACIDITY AND SUGAR CONTENT OF HARD RED SPRING WHEAT (From Milner, Christensen, and Geddes, 112)[a]

Moisture Content		Time in Respirometers	Respiratory Rate[a] (Final Day)	Mold Colonies	Respiratory Quotient	Germination	Fat Acidity	Total Sugars	Reducing Sugars
Initial	Final								
%	%	*days*	*mg./CO_2*	*per g.*	*(17th day)*	%	*mg.KOH/10g.*	*mg./10g.*	*(as % of total %)*
12.3	12.0	20	0.07	500	0.60	93	35.3	252	19.0
13.6	13.1	20	0.11	100	0.85	95	35.5	263	17.9
13.8	13.7	20	0.23	100	0.91	95	35.3	237	19.8
14.5	14.3	20	0.57	400	0.89	92	37.8	252	19.8
15.4	14.6	20	2.53	4,800	0.78	91	42.3	255	20.0
16.5	16.0	20	23.4	396,000	0.91	67	66.0	248	21.8
16.8	16.4	17	20.3	209,000	0.90	88	38.6	247	20.6
18.5	19.0	17	111.0	2,275,000	0.81	37	115.0	225	21.8
20.8	22.0	17	604.9	11,300,000	0.93	14	149.7	202	27.2
25.2	30.0	17	1,724.8	37,500,000	0.99	21	140.7	184	33.7

[a] Respiratory trials were conducted at 30°C. The values for mold count, germination, and chemical composition were determined on the wheat at the end of the respiration period.

eleventh day. In striking contrast, the respiratory rate of the sample treated with the highest concentration of sulfanilamide only increased from 33 to 43 mg. over the period of the trial. After 11 days' respiration this sample showed 84% germination in comparison with only 10% for the control.

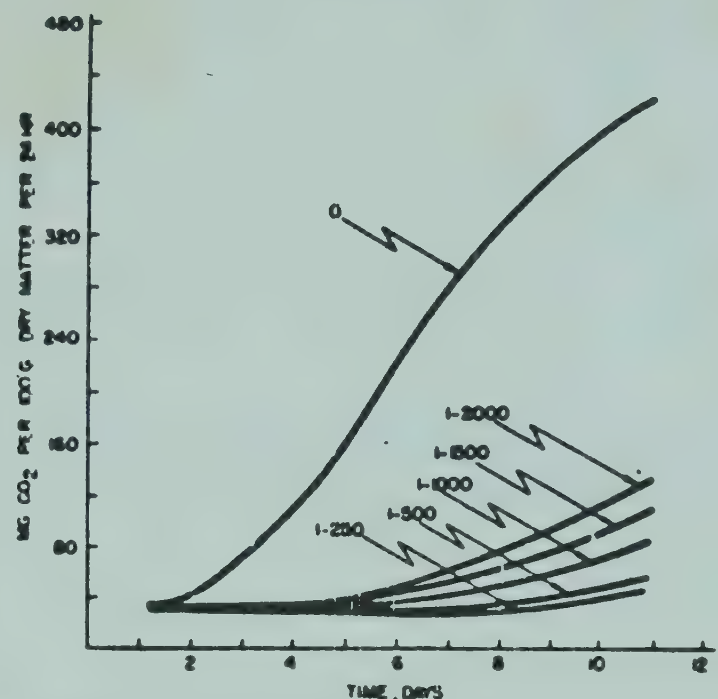

Fig. 4. Influence of various concentrations of powdered sulfanilamide on the respiratory behavior of wheat at 20% moisture (relative humidity, 90%) (from Milner, 109).

Studies (116, 160) have been made with autoclave-sterilized soybeans, at various moisture levels, subsequently inoculated with *Aspergillus flavus,* a mold which is indigenous to grain and which may proliferate strongly under damp storage conditions. Respiration data are shown in Figure 5. These beans show the same upward trend in respiration with time as do untreated beans stored at moisture levels which will permit mold growth. The low respiratory rates that are characteristic of normal seeds stored at low moisture values are naturally absent from beans killed by steam sterilizing. The low and relatively constant respiration of insect-free grain at moisture contents that preclude mold growth is due almost entirely to the biological processes of the seed itself, since the respiration due to the small mass of mold spores may be regarded as negligible. In experiments where mold counts have been made, the increase in respiration that occurs when the moisture content of the grain exceeds a certain range is accompanied by an increase in the mold population, an increase in fat acidity, changes in sugar content, and a marked decrease in viability (see Table 1).

The experiments which have been cited support the view that mold growth is mainly responsible for the high rate of respiration, the marked increase in fat acidity, and the loss in viability exhibited by grains when

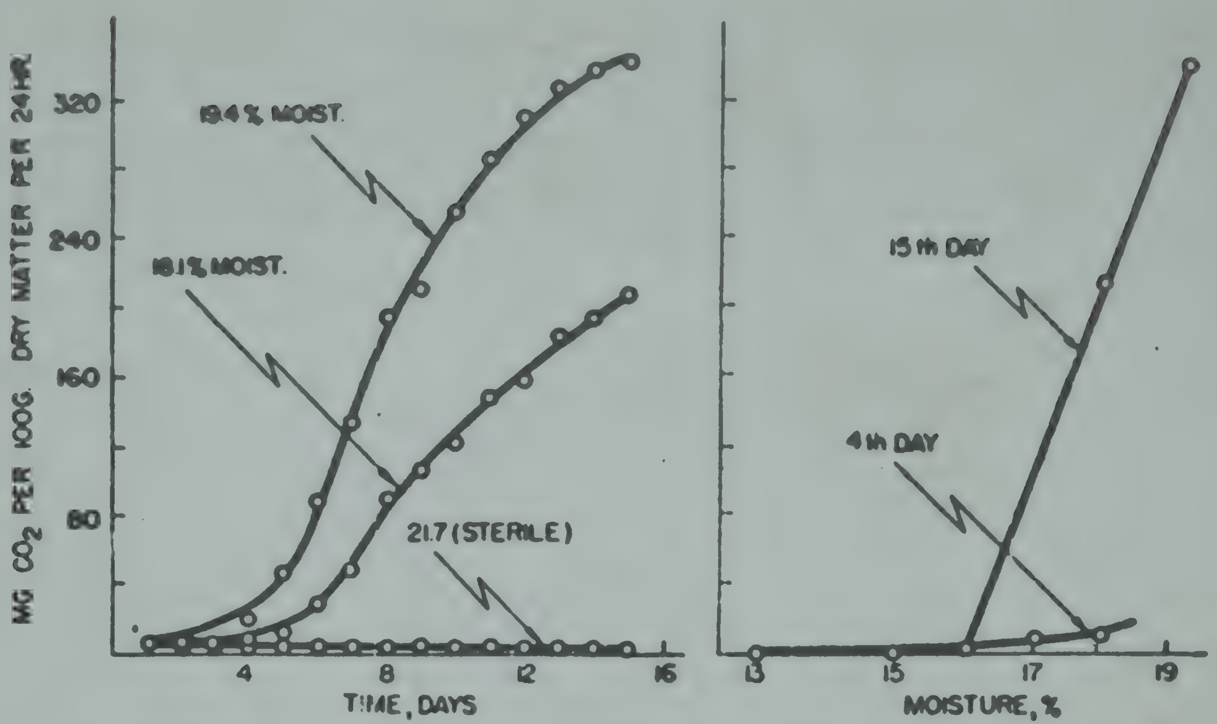

Fig. 5. Influence of time and moisture content on the respiratory rate of sterile soybeans inoculated with *Aspergillus flavus* at 37.8°C. (from Milner and Geddes, 116).

stored at moisture levels exceeding those in equilibrium with a relative humidity in excess of about 75%.

Influence of Moisture. In the preceding discussion it was pointed out that the moisture content of any particular grain is the main factor, along with temperature, which determines the intensity of respiration. The fact that the marked increases in respiration for different grains occur at a rather constant relative humidity of 75% in the interseed atmosphere, at which the equilibrium moisture content of different grains may vary markedly (14.0 to 14.5 for wheat, as compared with about 10.5% for flaxseed), clearly indicates that the total moisture content of the grain is not the controlling factor. On the contrary, only that part of the total water which is "free" to exert vapor pressure is significant, and the water "activity" (i.e., the vapor pressure of the moisture in the grain relative to that of pure water at the same temperature) must be approximately 0.75.

Many other phenomena observed in biological materials indicate that not all of the water present can function as "free" water and that some of it is "bound" or unavailable to serve as a solvent. Some of the water molecules are adsorbed on the surfaces of biocolloids and are held more rigidly and more closely packed than in water in the liquid state. Although several methods have been devised for estimating "bound" water in colloidal materials, many of them give different values when applied to the same systems. Accordingly, the fraction which is considered "free" is most conveniently defined in terms of the water-activity which is required to support a particular physiological function (62). This view

of the interpretation of data on bound water is of relatively recent origin.

In 1918, Bailey and Gurjar (16), who assumed that grain respiration was essentially due to the life processes of the embryo, employed the bound-water concept as a tentative explanation for the sharp increase in the respiration of wheat at moistures above 14.6%. Later, Bailey (14) demonstrated that changes in electrical properties of corn embryos closely paralleled the respiratory behavior in the region of the critical moisture zone for corn. He postulated that in this moisture range a continuous gel structure was formed which would permit ready diffusion of metabolites and end products to and from the seat of respiration. As recently as 1940, Kretovich and Ushakova (88), although suggesting that respiration of both grain and microorganisms is involved, concluded that the sharp upward trend in the carbon dioxide production of wheat at 15.5% moisture could be explained by an abrupt increase in the quantity of free water at this moisture content. Although no data were given for the bound water of wheat itself, determinations based on the color changes of cobalt chloride at a sharply defined water vapor pressure showed that wheat starch bound 11.8% water and wheat gliadin 19.4%.

The relationship of bound water to wheat respiration has been investigated by Shirk and Appleman (142) who measured the heat of fusion to determine the freezable and unfreezable water in wheat at various moisture levels. The unfreezable water ("bound") held by the grain increased gradually to a maximum at 21% total moisture. Although the respiration values rose only gradually with increases in moisture content over the range 15.6 to 31.2%, the greatest rise occurred at a moisture content of 21%. The investigators concluded that "the sharp acceleration of respiration in wheat grains when the total water content is increased above a certain minimum is due to a rather sudden increase in freezable water content relative to the other constituents of the cell system." The moisture level of 21% greatly exceeds that found to be critical for the storage of wheat by numerous investigators.

The fundamental relationship between moisture content and the respiratory activity of grain was only clarified when the prominent role played by microorganisms was clearly recognized. When the water "activity" reaches a level at which microorganisms will grow, the respiratory activity of the grain is supplemented by the much greater activity of the microflora. As has been pointed out by Gilman and Barron (60), the majority of the earlier workers overlooked the fact that the moisture content at which mold growth began was also the one at which they observed marked increases in carbon dioxide production. It is noteworthy, however, that in 1901, Kolkwitz (87) found that increased production of carbon dioxide by barley seeds at a moisture content between

15 and 16% could be materially lessened by treating the grain with toluene. Grinding the grain increased the respiration at moisture values above the critical level.

Numerous workers have studied the relation between moisture content and mold growth (55, 147). McHargue (100) reported that deterioration in stored corn was always associated with mold growth; molds did not appear on whole corn until a moisture content of 15% was reached, but corn meal showed mold growth at moistures as low as 12%. Thom and LeFevre (162) found that certain species of *Aspergilli* begin to grow on meal at moisture levels as low as 13%.

Nutrient availability, time, and temperature, all influence the threshold humidity at which molds will grow (53, 64, 145). Several investigators have studied the temperature-humidity interaction, and it appears that molds will germinate at lower relative humidities when maintained at their optimal temperatures; these vary between 25° and 30°C. for most species (22, 64, 65, 166). In studies on the growth of molds on several types of feeding-stuffs stored at various relative humidities for periods extending over more than 3 years, Snow, Crichton, and Wright (149) found that mold growth developed after a very prolonged latent period at relative humidities as low as 65%. When extensive mold growth occurs there is a marked increase in the moisture content of grain even though the interseed atmosphere is maintained at a lower equilibrium relative humidity (112, 116). This is illustrated by the data in Table I. The higher hygroscopicity of the moldy grain, which may be due to the mold mycelia or to decomposition products of the seed, results in the maintenance of more favorable conditions for mold growth.

From these and other researches, it may be concluded that the minimum relative humidity at which the mold species commonly found on grain will grow within a few weeks is about 75%; this corresponds to a rather wide range in moisture content. Bacterial growth is rarely encountered in stored grain, as the relative humidity requirement for these microorganisms exceeds 90% (69, 96, 169, 170, 171). Since mold growth is associated with heating and deterioration, the maximum moisture content for the safe, short-time, commercial storage of a given grain at ordinary temperatures can be approximated by ascertaining its equilibrium moisture value when exposed to an atmosphere of 75% relative humidity. If the grain is cracked or broken, or if the storage is prolonged, or at high temperatures, the maximum moisture limit should correspond to a lower relative humidity. For short-time (8 months) storage of products that are most susceptible to molding (such as locust beans, wheat bran, and Scotch beans), Snow (148) has suggested that the relative humidity should not exceed 72%; for long-time storage (up to 2 or 3 years),

a relative humidity as low as 65% must be accepted as a safe maximum. Typical hygroscopic moisture values for various grains maintained in an atmosphere of 75% relative humidity are assembled in Table II.

The relative humidity of the interseed atmosphere in equilibrium with grain of a given moisture content is not greatly influenced by temperature. However, as adsorption is characterized by a negative temperature coefficient, there is a slight increase in relative humidity as the temperature is raised. In other words, at a given relative humidity the hygroscopic moisture increases slightly as the temperature is lowered. This effect only amounts to about 0.6 to 0.7% moisture increase for each 10°C. drop in temperature (57, 59).

Although the relationship between respiratory activity and moisture content has not been determined for all the seed species listed in Table II, it nevertheless follows from the above discussion that the equilibrium hygroscopic moisture value in an atmosphere of 75% relative humidity is a useful general index of the maximum safe storage moisture for the crop in question—subject, of course, to certain variables such as commercial quality, physical damage, and prior history (e.g., weathering, wetting, and drying, etc.). Data which support this contention that respiratory increases are initiated at moisture values in equilibrium with relative humidity values of 74–75% are available for barley (15), corn (15), cottonseed (41), flaxseed (139), rye (15), soybeans (116), sunflowerseeds (95), and wheat (112).

Influence of Temperature. Respiration, whether of seeds, molds, or insects, depends upon chemical reactions and is therefore accelerated by an increase in temperature until it is limited by such factors as the thermal inactivation of the enzymes which are involved, exhaustion of substrate, limitation in oxygen supply, or accumulation of inhibitory concentrations of carbon dioxide. In addition, the effect of temperature on respiratory rate will depend upon the moisture content of the seeds. It will also depend upon the relative contributions of seeds, molds, and insects to the total respiration, because of variable effects of temperature on these factors. When only the evolved carbon dioxide is measured, the apparent respiration may be influenced by the liberation of "bound" carbon dioxide and by the thermal decomposition of organic compounds with or without the interaction of oxygen. The interrelation of the different variables is so complex that empirical determinations of optimum temperatures for grain respiration yield only approximate values and cannot be applied to conditions other than those under which the values were determined.

Many investigators have shown that the rate of respiration of plants increases with the temperature until inhibition of the vital processes

TABLE II

HYGROSCOPIC MOISTURE VALUES FOR DIFFERENT GRAINS AT 75% RELATIVE HUMIDITY

Grain	Moisture Content[a]	Temperature of Measurement	Reference
	%		
Barley	14.4	25°–28°C.	Coleman and Fellows (44)
Buckwheat	15.0	25°–28°C.	Coleman and Fellows (44)
Corn	14.3	25°C.	Bailey (14)
Corn	14.4	25°–28°C.	Coleman and Fellows (44)
Corn	14.7	80°F.	Brockington, Dorin, and Howerton (28)
Cottonseed —			
Whole seed	11.4	25°C.	Karon (78)
Meats	10.0	25°C.	Karon (78)
Hulls	13.7	25°C.	Karon (78)
Flaxseed	10.0	25°–28°C.	Coleman and Fellows (44)
Flaxseed	10.3	25°C.	Larmour, Sallans, and Craig (94)
Flaxseed	10.5	28°–30°C.	Schricker (139)
Oats —			
Whole seed	13.9	25°–28°C.	Coleman and Fellows (44)
Whole seed	13.4	25°C.	Colvin, Craig, and Sallans (46)
Groats	14.1	25°C.	Colvin, Craig, and Sallans (46)
Hulls	12.7	25°C.	Colvin, Craig, and Sallans (46)
Peanuts —			
Whole	10.5	25°C.	Karon and Hillery (82)
Kernels	8.8	25°C.	Karon and Hillery (82)
Rice —			
Whole seed	14.4	25°–28°C.	Coleman and Fellows (44)
Whole seed	14.0	25°C.	Karon and Adams (79)
Artificially dried	13.2	25°C.	Karon and Adams (79)
Polished	15.6	25°C.	Karon and Adams (79)
Rye	14.9	25°–28°C.	Coleman and Fellows (44)
Sorghum	15.3	25°–28°C.	Coleman, Rothgeb, and Fellows (45)
Soybeans	14.4	25°C.	Ramstad and Geddes (134)
Soybeans	14.0	25°C.	Larmour, Sallans, and Craig (94)
Sunflowerseed —			
Whole seed	10.4	25°C.	Larmour, Sallans, and Craig (94)
Whole seed	11.7	25°C.	Colvin, Craig, and Sallans (46)
Meats	8.2	25°C.	Colvin, Craig, and Sallans (46)
Hulls	14.6	25°C.	Colvin, Craig, and Sallans (46)
Wheat —			
Hard red winter	14.6	25°–28°C.	Coleman and Fellows (44)
Hard red spring	14.8	25°–28°C.	Coleman and Fellows (44)
White	15.0	25°–28°C.	Coleman and Fellows (44)
Durum	14.1	25°–28°C.	Coleman and Fellows (44)
Soft red winter	14.7	25°–28°C.	Coleman and Fellows (44)
Wheat —			
Weak	16.1	10°C.	Gane (57)
Medium	15.3	10°C.	Gane (57)
Strong	15.4	10°C.	Gane (57)
Wheat	14.5		Pap (129)
Wheat	15.0	70°F.	Robertson, Lute, and Gardner (135)
Wheat	15.5	....	Hoffmann (73)
Wheat	14.7	80°F.	Gay (59)

[a] Calculated to damp weight basis.

begins. Researches on various species of plants and on various types of plant tissues have been summarized by Miller (107). Only those investigations that deal with grain will be reviewed here. In 1890, Clausen (42) reported the optimum temperature for the respiration of germinating wheat to be about 40°C. The rate of respiration was 2.86 times as great at 10°C. as at 0°C., and 1.09 times as great at 40°C. as at 30°C., with an average temperature coefficient of 2.71 between 0° and 40°C. Qvam (133) found that the rate of respiration of moist wheat increased up to at least 45°C., the highest temperature at which observations were apparently made.

Bailey and Gurjar (16) studied the respiration of hard red spring wheat containing 15.0% moisture at temperatures between 4°C. and 75°C. The grain was sealed in jars for 4 days at the desired temperature, and the accumulated carbon dioxide was then measured. Their data, reproduced below, showed that maximum respiratory activity occurred at 55°C., above which the rate fell off sharply:

Temperature, °C.	*Respiration[a], mg.*
4	0.2
25	0.4
35	1.3
45	6.6
55	31.7
65	15.7
75	10.3

[a] Carbon dioxide in mg. per 100 g. dry matter per 24 hours.

Milner and Geddes (115) studied the influence of temperatures, from 25° to 45°C., on the respiratory activity of soybeans initially containing 18.5% moisture. Under conditions of optimum aeration the equilibrium respiration rates were as follows:

Temperature, °C.	*Respiration[a], mg.*
25	33.6
30	39.7
35	71.8
40	154.7
45	13.1

[a] Carbon dioxide in mg. per 100 g. dry matter per 24 hours.

The respiration increased rapidly as the temperature was increased from 30° to 40°C., above which there was marked inhibition, the rate at 45°C. being less than one-tenth that at 40°C.

Milner and Geddes (115) found a lower temperature optimum for soybeans than the value Bailey and Gurjar (16) obtained for wheat. Aside from the fact that the values relate to different crops, they are not strictly comparable. Those reported by Milner and Geddes represent an

equilibrium condition after several days of widely varying respiratory rate characterized by a sharp acceleration followed by a slower decrease to a uniform value. The data of Bailey and Gurjar (16), on the other hand, were calculated mean values of cumulative carbon dioxide production in a sealed container obtained over only a few days of incubation. Milner (108) noted that a considerable portion of the "respiration" at temperatures of 37°C. and higher is apparently due to nonbiological oxidation of the organic constituents of the seed. For this reason the respiration studies of Milner *et al.* (112) with wheat were carried out at 30°C. where no significant amount of nonbiological oxidation is to be expected. Confirmation of the fact that carbon dioxide production from wheat due to chemical processes can occur at relatively low temperatures appears in the recent study of Milthorpe and Robertson (119).

The effects of aeration and temperature on the temperature coefficient of respiration, for 5° intervals, are shown in Table III for temperatures between 25° and 45°C. An increase in temperature coefficient with aeration appears between 30°–35°C. and 35°–40°C., but not between 25°–30°C. and 40°–45°C. In the last case thermal inhibition of respiration increased with aeration.

TABLE III

EFFECT OF AERATION ON THE ACCELERATION OF RESPIRATION UPON INCREASING THE TEMPERATURE BY INCREMENTS OF 5°C. (From Milner and Geddes, 115)
Wisconsin Manchu soybeans, initially conditioned to 18.5% moisture

Aeration Rate per Day	Temperature Coefficient[a] for Temp. Interval			
	25°-30°C.	30°-35°C.	35°-40°C.	40°-45°C.
ml.				
250	1.25	1.22	1.14	0.32
500	1.25	1.69	1.50	0.15
1000	1.11	1.84	1.94	0.10
1500	1.07	1.99	2.06	0.09
2000	1.18	1.81	2.15	0.08

[a] Temperature coefficients are based on respiration values for days when approximate respiratory equilibrium was obtained.

In adiabatic studies of the heating of soybeans containing 20.4% moisture, Milner and Geddes (117) found that respiratory inhibition due to thermal destruction of the fungi began at 50°C. Seed viability was destroyed at lower temperatures, usually about 45°C. Both of these temperatures no doubt depend on the moisture content of the seeds and upon the rate at which temperatures rose to the specified levels.

Under practical conditions, low storage temperatures are desirable since they inhibit mold growth. Damp grain placed in storage at the low winter temperatures which prevail in Canada and in certain sections of the United States may be held for several months with little deterioration due to respiration or heating. The relatively insignificant effect of external atmospheric temperatures upon the interior temperatures of large bulks of grain has been noted by Agronomoff (1) and Robertson and Milthorpe (137). Babbitt (10) has concluded, from heat conductivity data and thermodynamic considerations, that external seasonal temperature variations do not affect the temperature of the grain mass at depths below 24 ft. On the other hand, even small temperature gradients within the mass of grain, whether due to external or internal causes, may be directly responsible for several phenomena leading to grain spoilage (see page 209).

Influence of Aeration; Aerobic and Anaerobic Respiration. The oxygen and carbon dioxide contents of the interseed atmosphere influence the rate of respiration of grain and consequently the rate of deterioration and heating. Many authors have shown that inadequate aeration and accumulation of carbon dioxide repress the respiration of plants and seeds, although, as was first shown by Rollo in 1709 (according to Kidd, 83), carbon dioxide is produced by plant tissues even under anaerobic conditions.

In 1896, Mangin (102) germinated seeds in closed trains through which the atmosphere was recirculated. He found a decrease in the respiratory activity and an increase in the respiratory quotient with partial vitiation of the air. Takahashi (156) reported that rice can germinate in water in the complete absence of air. This unique characteristic is due to a well-developed anaerobic respiratory mechanism not present in other cereals (159). In determining the rates of respiration of sterilized wheat in continuous currents of air, hydrogen, or nitrogen, Hill (70) found that the rate in air was about twice that in the other two gases for seeds sterilized in alcohol, and about 20% greater for seeds sterilized in formalin.

Kidd (83) showed that various concentrations of carbon dioxide depressed the respiration of germinating seeds in an anaerobic atmosphere in the same order as they did when oxygen was present. He concluded that seeds have two types of respiration, one depending on oxygen and not affected by carbon dioxide, and the other depending on an anaerobic system which is affected by carbon dioxide. He believed that dormancy in seeds is "primarily a phase of narcosis induced by the action of carbon dioxide." Freitinger (54) believed that dormant seeds respire mainly by means of an intramolecular or anaerobic system, for the seed coats

hinder the penetration of atmospheric oxygen to the respiring centers. This anaerobic condition is terminated when the swelling associated with germination ruptures the seed coat. Taylor (159) noted that rice will germinate and grow better than wheat under low oxygen tensions and associated this observation with the fact that rice is subject to an oxygen-impoverished environment during its early growth under water. Thornton (164) found that the germination of most seeds is not inhibited by carbon dioxide concentrations below 20%, nor the growth of seedlings by concentrations under 10%. He regarded oxygen deficiency as the most likely cause of inhibited germination. Later, he extended the causes of dormancy to include the accumulation of inhibitory substances within the seed. The structure of the seed coat, and the temperature, moisture, and carbon dioxide concentration of the interseed atmosphere may be contributory factors (165).

The researches which have been cited have dealt primarily with the effect of atmospheric composition on germinating seeds in which the moisture content and respiratory rates greatly exceed those encountered in stored grain. Bailey and Gurjar (16) investigated the carbon dioxide production of wheat (15.6 and 17.6% moisture) in air and in nitrogen with the following results:

	Respiration[a] *at 23.9 °C.*	
Moisture, %	*Air, mg.*	*Nitrogen, mg.*
15.6	1.1	0.4
17.6	6.8	2.8

[a] Carbon dioxide in mg. per 100 g. dry matter per 24 hours.

The respiratory activity in nitrogen was only about 40% of that in air.

Milner and Geddes (115) studied the influence of various aeration levels on the respiration rate of high-moisture soybeans at a series of temperatures between 25°C. and 45°C. In these experiments, 250 g. of soybeans containing 18.5% moisture were aerated continuously at five rates, varying from 250 to 2000 ml. per day. Nitrogen containing 0.21% oxygen was also used. The concentration of the carbon dioxide present in the interseed atmosphere as a result of the respiration of the grain was thus varied over wide limits. Typical effects of aeration and time on the respiratory rates at 40°C. are shown in Figure 6. Under nitrogen the respiratory activity was extremely low and remained constant over the period of the treatment. In contrast, the respiration of the aerated samples increased slowly at first, then rapidly, and finally tended to level off at values which depended upon the rate of aeration. That anaerobic respiration occurred under nitrogen was indicated by high

respiratory quotients of from 3 to 23. The rate of respiration was only 3% of the maximum attained in air, and its constancy over the 19-day period implies that only seed respiration is involved. Limited aeration extends the latent period before mold growth commences, and decreases the maximum respiratory rate eventually attained.

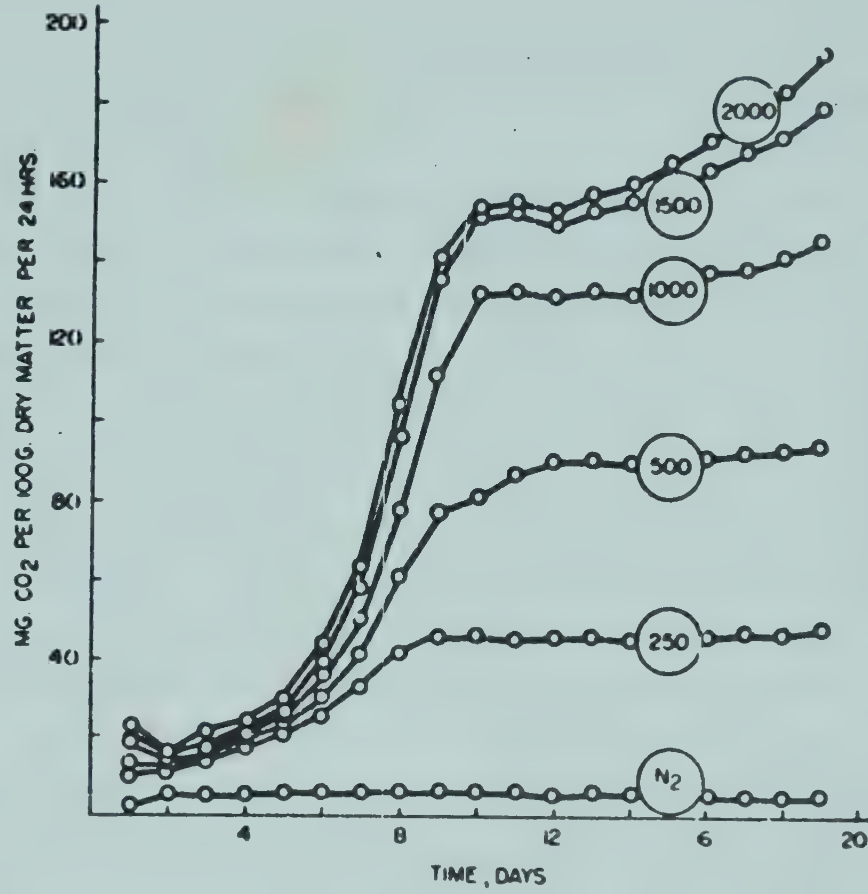

Fig. 6. Influence of time and aeration on the respiratory rate of Wisconsin Manchu soybeans at 19.1% moisture and 40°C. The daily rates of continuous ventilation were: 250 ml. of nitrogen (0.2% oxygen) and 250, 500, 1,000, 1,500, and 2,000 ml. of air (from Milner and Geddes, 115).

Respiratory inhibition of soybeans occurred when interseed carbon dioxide concentrations exceeded a range of 12 to 14%. Under such inhibitory conditions, the apparent temperature coefficient of respiration was lowered and the respiratory quotients decreased from 1.0 to about 0.85—the latter value being that under severe suppression of respiration. Similar studies with wheat (112) indicated that the respiration of this grain at elevated moisture levels was somewhat more sensitive to inhibition by carbon dioxide. A decrease in respiration was apparent when 7% of carbon dioxide was present and became more marked at carbon dioxide values in excess of 12%. Wheat which was damp enough to support mold growth also differed from soybeans in that the initial respiratory quotient attributable to seed respiration was about unity, and tended to fall towards 0.8 as the mold growth and respiration increased with time. The respiration of soybeans at moisture contents lower than those required for mold growth is characterized by respiratory quotients well below unity.

The fact that the maximum respiration of grain with its accompanying fungi (and sometimes insects) requires adequate aeration is of considerable commercial significance. Many elevator operators believe that stored grain, even though it is not heating, should be "turned" or ventilated at intervals, and even that grain must "breathe" (i.e., have access to oxygen) to retain its quality in storage. On the other hand, some authorities have strongly advocated hermetically sealed storage (168). The turning of grain by transferring it on open conveyors from one bin to another, especially when low atmospheric temperatures prevail, will cool heating grain and will also permit an exchange of water vapor, oxygen, and carbon dioxide. The exchange of water vapor is extremely slow, and if the atmospheric humidity is high, the moisture content of the grain may be slightly increased rather than decreased. Unless grain in bulk storage is respiring rapidly enough to be in imminent danger of heating, or is actually heating in certain areas, there is no apparent advantage to be gained by turning the grain. Experiments discussed elsewhere in this chapter indicate that seed viability is maintained, even in rather low concentrations of oxygen and relatively high concentrations of carbon dioxide, provided that moisture contents and temperatures are low.

The advocates of hermetic or airtight storage point out that accumulation of carbon dioxide and depletion of oxygen in the interseed atmosphere, as a result of the various respiratory processes, may well be advantageous. It is claimed that a point is reached at which mold growth, insect development, and heating in grain stored at relatively high moisture contents are prevented. In dry grain, the various deteriorative processes doubtless will be retarded, and the entrance of insects and rodents, and the absorption of water vapor by dry grain from a moist atmosphere, will be prevented (51, 168). Replacement of the interseed air with an inert gas at the time of storage would be an even more effective means of limiting the deteriorative changes and might have particular merit with hard wheats destined for bread flour production. Such flours, especially those milled from U.S. hard winter wheats, frequently require artificial maturation with small quantities of oxidizing agents to secure optimum baking results. The natural aging of wheat requires a downward adjustment of the treatment as the season advances, and more satisfactory results might conceivably be obtained if natural aging were prevented. The optimum dosage of oxidizing agents could then be accurately established for each class and protein range of wheat at the beginning of a crop year. Facilities for the storage of wheat on a commercial scale under inert atmospheres have recently been placed in operation (58), although sufficient experi-

ence has not yet been gained to determine the advantage of this practice.

While airtight and inert gas storage may have attractive advantages, these must be weighed against the danger of deterioration due to anaerobic respiration. Anaerobic respiration soon produces dead grain, which is much more readily attacked by molds and deteriorates more rapidly than viable grain. It is quite generally recognized that anaerobic respiration increases with increasing moisture content, and that airtight storage cannot be recommended for high-moisture grain. Such grain, although it does not heat when stored anaerobically, goes out of condition rapidly. Thus Matz and Milner (104a) observed that protracted storage of damp wheat under anaerobic conditions where mold growth is inhibited appeared to be more damaging to baking quality than storage in an oxygen atmosphere. The wheat stored anaerobically also contained more kernels classified by grain inspectors as damaged than did the grain stored in the presence of oxygen.

In studies with corn, Bottomley, Christensen, and Geddes (27) recently showed that some molds, particularly *Penicillium* sp. and *Candida pseudotropicalis*, are surprisingly tolerant of very low oxygen tensions. Moreover, yeasts that are invariably present bring about fermentation with the production of alcohols and acids, so that grain stored anaerobically will soon become sour if the moisture content and temperature are sufficiently high. It is questionable whether the maximum moisture limit for the safe storage of various grains, even for short times, could be increased by using anaerobic conditions. An answer to this question can only be obtained by controlled experiments with various grains stored at different moisture contents under aerobic and anaerobic conditions. While dry grain can probably be safely stored under airtight conditions, such grain does not represent a storage hazard over normal storage periods.

The advantages and disadvantages of natural ventilation of grain and of airtight storage have also been discussed by Oxley (126) who holds similar views to those presented here.

Influence of Prior History. The storage properties of grain are influenced by environmental conditions during growth and maturation, by the degree of maturity at harvest, by methods of harvesting, and by the handling the seed has received until it is placed in storage (14, 15, 16, 45, 87, 116, 118, 123, 134, 160). Varietal differences in cereal grains may also influence their relative respiratory rates; softer types of wheat will respire more rapidly than harder types at similar moisture levels and temperatures (16).

Physical damage to the seed coat from any cause, such as mechanical damage from threshing, from elevator handling, or from insect attack,

increases the storage hazard. Many workers have shown that cracked and broken kernels respire more rapidly than whole kernels under the same conditions. Physical injury also provides more ready access of fungi to the nutrients of the seed, with the result that the grain will respire more vigorously and lose its viability more rapidly. In general, the lower the commercial grade, the greater is the storage hazard. Frost before maturity arrests the synthetic processes in the grains, and frost-damaged seed, even though of low viability, will respire more rapidly than sound seed. Frost-damaged grain usually contains higher percentages of nonprotein nitrogen and reducing sugars, and is more heavily contaminated with microflora, than mature, sound seed (108, 118). This is well illustrated by the data in Table IV obtained in a study of frost-damaged soybeans by workers at the Minnesota Agricultural Experiment Station.

TABLE IV

RELATION BETWEEN EXTENT OF FROST-DAMAGE, VIABILITY, CHEMICAL COMPOSITION, MOLD INFECTION, AND RESPIRATION OF SOYBEANS
(Compiled from Milner, 108, and Milner *et al.*, 118)

Damaged Seeds	Germination	Seeds Infested by Internal Microflora[a]	Oil Acidity[b]	Nonprotein Nitrogen[c]	Sugars[d]		Respiration[e]
					Reducing	Nonreducing	
%	%	%	mg.	mg./10g.	mg./10g.	mg./10g.	mg.
10.3	53	30	15.6	13.9	65	279	107
13.3	44	23	19.4	30.6	78	284	112
21.0	27	50	17.9	29.7	81	247	185
26.0	29	51	17.8	32.6	83	263	238
41.0	14	58	19.4	35.2	81	275	239
55.0	5	73	28.8	45.9	110	229	357

[a] Seeds were surface-sterilized and plated on sterile nutrient agar.

[b] Mg. KOH per 10 g. of oil; determined by the method of Zeleny and Coleman (178).

[c] Determined by the trichloroacetic acid method described by Becker, Milner, and Nagel (23).

[d] Reducing and nonreducing sugars were estimated by the alkali-ferricyanide method described for wheat flour by the American Association of Cereal Chemists.

[e] Respiration is expressed as mg. CO_2 produced by 100 g. of beans containing 15.9 ($\pm$0.1%) moisture in 24 hours as determined by the continuous aeration technic of Milner and Geddes (115).

A period of prolonged humidity in the preharvest season will probably be reflected in the storage properties of subsequently mature grain crops. Though there is little specific evidence bearing on this point, it seems logical to suggest that such conditions favor the proliferation of mold mycelia under the seed coat (such as has been described in the literature, 112, 126, 128) prior to final desiccation. This increased infection, dormant in dry grain, may be responsible for the greater ten-

dency of some grain to respire and heat when dampened than other similar material of the same commercial quality. For instance, the best quality soybeans of the 1942 crop, which matured after a prolonged cold, wet harvest period, heated and respired more rapidly when dampened than grain of the same commercial quality obtained in the following year when maturing and harvest conditions were ideally dry (108).

Other studies (115, 123, 160) indicate that viable seeds resist the inroads of storage fungi. For example, the respiratory rate of a sample of soybeans containing 19% moisture attained values of about 80 mg. carbon dioxide at 30°C. and about 200 mg. at 40°C., due to the combined respiration of the seeds and the molds. By exposure for 8 days to a temperature of 50°C. the seeds were killed, and the mold respiration was markedly inhibited; however, a considerable survival of mold spores occurred. On re-establishment of a temperature of 30°C., very rapid respiratory increases occurred almost immediately, coincident with mold growth, and after only 9 days a respiratory rate of nearly 500 mg. carbon dioxide was reached. This respiratory rate, due to the mold population, was over six times greater than the maximum rate of respiration attained by the same seed, and its molds, when the seed was viable.

The increased susceptibility of heat-injured seeds to the inroads of fungi, whose growth promotes rapid respiration and heating, finds its counterpart in a practical storage problem. It has been noted that very damp corn (e.g., 25% moisture) which has not been dried may heat in storage less rapidly than the same corn which has been dried to a moisture of 18% at air temperatures which are damaging to seed viability, and which may cause small fissures or cracks in the seed coats through too rapid drying. It is also recognized that commercial grain, which has been dried to safe moisture limits, when allowed to rehydrate in a humid atmosphere may begin to respire and heat at lower moisture values and to a greater extent than undried grain at similar moisture values.

Effect of Chemical Treatment on Respiration

Drying grain to a moisture level which will give an equilibrium relative humidity in the interseed air of less than 75% is the most effective method of preventing excessive respiration and heating. However, several workers have explored the possibility of prolonging the storage life of damp grain by chemical treatments that inhibit mold growth. Both gaseous and solid fungistatic agents have been tried, and the results of these researches will be reviewed in this section.

Gaseous Preservatives. The repressive action of toluene on wheat respiration was noted by Kolkwitz (87) in 1901 and was tested in 1935 by Larmour, Clayton, and Wrenshall (93). They found that the vapors of both toluene and carbon tetrachloride effectively controlled the growth of fungi on damp wheat and greatly decreased its respiratory rate. In fact, no heating occurred in 15-pound samples of wheat containing 25% moisture. Both agents, especially toluene, decreased the viability of the seeds, particularly at high moisture contents. Subsequent studies by Larmour and Bergsteinsson (92) showed that the milling and baking qualities of wheat at 18 and 24% moisture contents were damaged by storage at 21°C. for periods longer than 4 weeks. The damage was more pronounced with carbon tetrachloride than with toluene vapor; in such damp grain the carbon tetrachloride rapidly disappeared and the grain became sour. Tomkins (167) studied the inhibitory effect on mold growth of various volatile substances including ethanol, acetone, formaldehyde, chloroform, acetal, diethyl ether, amyl formate, hydrogen cyanide, hydrogen sulfide, sulfur dioxide, and ammonia. Some of these lengthened the incubation period but had little effect on growth rate, while others had no influence on the incubation period but depressed the growth rate. Ammonia both delayed the appearance of molds and retarded their growth. The effectiveness of the various inhibitors increased with temperature.

The effect of various chemicals on the respiration and heating of high-moisture cottonseed was studied by Malowan (101) who found that high concentrations of acetic acid, ethanol, and formalin inhibited respiration.

Cameron (32) studied the effectiveness of several organic compounds in controlling mold growth on sunflowerseed as measured by the number of days over which respiration remained at a low and relatively constant rate. The various chemicals were applied at a concentration of about 0.3% of the dry weight of grain. The volatile compounds which she tested were sorted into three classes on the basis of their fungicidal properties and their toxicity to the seed as follows:

Class I. Relatively ineffective against fungi and of low toxicity to the sunflowerseed embryo: ether, cyclohexane, ligroin, carbon tetrachloride.

Class II. Good mold inhibitors but toxic to the seed embryo: acetone, 1,4-dioxan, methyl furan, absolute ethanol.

Class III. Effective fungicides, with a limited influence on seed viability: benzene, trichlorethylene, chloroform.

Trichlorethylene was the most promising of these volatile liquids. It was an excellent mold inhibitor, but when damp wheat was treated

with it, the odor was carried over into the flour, though not into the bread. Although the trichlorethylene did not influence loaf volume, all treated samples exhibited a markedly darker crumb color.

Altschul and his associates (2, 3, 4, 6, 7, 80, 89) have carried out extensive experiments on the value of ammonia for preventing the deterioration of cottonseed in storage. In laboratory experiments they found that when the hydrogen-ion concentration of normal seeds, which ranges from pH 6.5 to 7.0, was raised by means of ammonia to about pH 8, or lowered with hydrogen chloride to pH 4.6, the formation of free fatty acids and the respiratory rate were greatly inhibited. Early pilot-scale tests with one-ton lots of cottonseed indicated that treatment with 10 pounds of gaseous ammonia was sufficient to bring the pH of a water extract of the seeds to 8.0 and effectively inhibited lipolysis and heating. The treatment, however, resulted in an initial increase in temperature, but after this heat was dissipated, the ammonia-treated seeds remained at a lower temperature than the untreated seeds. This observation paralleled their finding that ammonia treatment of cottonseed caused an initial stimulation in respiration followed by a partial inhibition, with the result that the average respiration was lower than that of untreated seed. Later, plant-scale tests, involving the treatment of 30-ton lots of cottonseed with ammonia, showed that the initial heating resulted in sufficient damage to preclude the use of this agent in commercial storage. Moreover, the ammonia treatment of immature seeds stimulated rather than repressed lipolysis. Inhibition of the lipolysis was not as effective for seeds which had already begun to deteriorate as for sound seeds.

Ethylene oxide has been recommended as a fumigant against insects (12) and has been shown to be useful in preventing microbiological deterioration in dried fruits (173); but its effectiveness as a fungistatic agent in grain remains to be determined. The mycostatic properties of other common grain fumigants, such as methyl bromide, have not been explored.

The preservative effect for damp wheat of over 100 organic compounds, including solids, liquids, and vapors, was investigated by Matz and Milner (104a). The commercial quality of the grain was evaluated by licensed inspectors; milling and baking tests were also made. In preliminary storage studies, several gaseous agents, carbon tetrachloride, chlorotrifluoroethymethyl ether, nitrogen trichloride, chlorine dioxide, and propylene oxide, prolonged the appearance of soundness in damp grain. Of these, propylene oxide was the most effective in inhibiting respiration, but it markedly decreased the viability of the grain. None of the treatments completely prevented undesirable changes in the bak-

ing quality of wheat stored at high moisture content. The loaves had a musty odor and a gray color; many showed drastic changes in the response to the inclusion of potassium bromate in the baking formula, as well as marked differences in the farinograph curves. In several cases, however, chemical treatment lessened the deleterious changes and some treatments, such as a mixture of propylene oxide and carbon tetrachloride, actually resulted in greater loaf volume. Since deleterious changes occur in damp wheat in spite of treatment with fungistatic agents, particularly under anaerobic conditions, the authors concluded that chemical preservation of damp wheat cannot yet be recommended as a practical measure.

Several gaseous agents, such as chlorinated hydrocarbons, are fungistatic rather than fungicidal, so that mold growth may quickly be re-established in damp grain if an effective concentration of these gases is not maintained. Some reduction in the viability of damp grain is to be expected as a result of treatment with gaseous fumigants.

Solid Preservatives. Several investigators have studied the possibility of controlling the deterioration of high-moisture grain in storage by mixing it with solid preservatives. Sodium chloride appears to be one of the first compounds to have been tried. In 1915, Barrow (20) found that the treatment of cottonseed with 5% by weight of sodium chloride minimized heating and deterioration in storage. He attributed the effect to the extraction of moisture from the seeds by the salt, which permitted the salt to dissolve, penetrate the seed coat, and inhibit the action of enzymes and microorganisms within the seed. Similarly, attempts have been made to control the heating of hay by the addition of salt (143), and salt has long been used to check mold growth on damp corn.

Cameron (32) studied the effect of treating high-moisture sunflowerseed with various solid fungicides, the majority of which were applied in ether solutions at a concentration of about 0.3% of the dry weight of the seed. Of the several compounds which were investigated, the most effective in suppressing mold growth were diacetyl, phenothiazine, and 8-hydroxyquinoline, and they did not appear to be toxic to the embryo. In addition, five water-soluble fungicides (sodium salicylate and benzoic, boric, butyric, and salicylic acids) were studied by conditioning grain samples with water solutions to give concentrations of 0.06 to 0.25% of the dry weight of the seeds. Of these, butyric acid was the only one that effectively suppressed mold growth.

Snow and Watts (151, 152) investigated the utility of various sulfa drugs in the storage of linseed cake at high humidities. Sulfanilamide and propamidine incorporated with ground linseed cake, in nontherapeutic concentrations of about 0.2%, greatly suppressed mold growth

and prolonged the storage life of the product. The effectiveness of sulfanilamide was confirmed by Milner (109) who found that concentrations as low as one part per 2000 parts of wheat markedly inhibited mold growth and respiration when the grain was maintained at elevated moisture levels. The sulfanilamide had little influence on the viability of the grain. In further studies, Milner, Christensen, and Geddes (113) carried out preliminary screening tests on the fungistatic properties of more than 100 organic compounds. The compounds were dusted on moist wheat in concentrations of about one part by weight of dust to from 100 to 1,000 parts by weight of wheat, and the treated samples were examined at intervals for mold growth. Relatively few of the compounds prevented visible development of mold. Even some compounds that are known to be toxic to certain fungi — such as calcium propionate, sodium N-chlorobenzene sulfonamide (chloramine B), sodium alkyl aryl sulfonate (Nacconal N R), and tetrachloro-para-benzoquinone (Spergon) — did not prevent the visible development of molds on the moist grain. Some fungicides inhibited certain molds, but not others, and some fungicides which prevented mold growth also killed the seed. Eight of the most promising compounds were dusted on wheat containing 20% moisture at a rate of one part per 1000 parts of grain, and respiration trials were conducted over a 10-day period with the results shown in Figure 7.

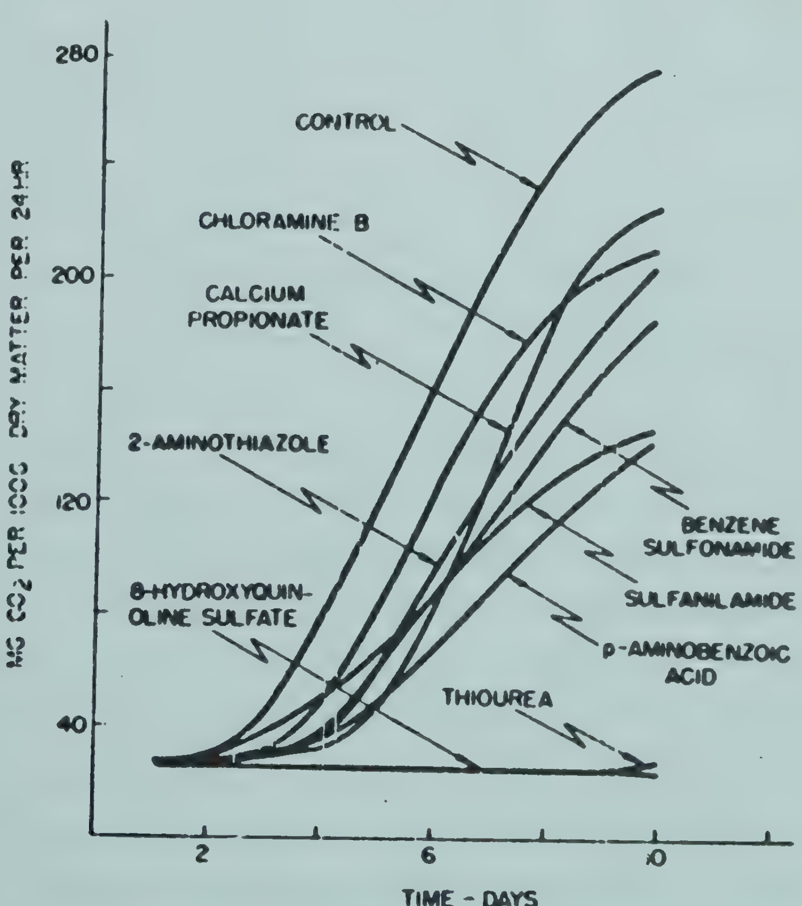

Fig. 7. Influence of time and various mold inhibitors on the respiratory rate of Regent wheat at 30°C. containing 20% moisture. The inhibitors were used at a concentration of 1:1,000 (from Milner, Christensen, and Geddes, 113).

The mold count, fat acidity, and viability of the samples at the end of the respiration trial, recorded in Table V, show that the most efficient preservatives in order of decreasing value are: 8-hydroxyquinoline sulfate, thiourea, p-aminobenzoic acid, sulfanilamide, benzene sulfonamide, 2-aminothiazole, sodium N-chloro-benzenesulfonamide (chloramine B), and calcium propionate. In general, respiration and fat acidity decreased with a decrease in mold population, while the percentage of viable seeds increased. Of the two most effective compounds, thiourea was only slightly toxic to wheat at moisture contents below 24%, while 8-hydroxyquinoline sulfate reduced germination more than 30%.

TABLE V

INFLUENCE OF VARIOUS FUNGISTATIC AGENTS ON RESPIRATORY RATE, FAT ACIDITY, GERMINATION, AND MOLD GROWTH IN WHEAT CONTAINING 20.0% MOISTURE
(From Milner, Christensen, and Geddes, 113)

Samples analyzed after completion of 10-day respiration trials at 30°C.

Treatment	Respiratory Rate[a]	Fat Acidity[b]	Germination[c]	Mold Colonies per Gram
			%	
Control	273.0	77.0	18	6,950,000
Calcium propionate	224.8	91.7	15	4,320,000
Chloramine B	208.6	95.8	21	3,170,000
2-Aminothiazole	202.8	75.3	17	....
Benzene sulfonamide	185.5	52.0	27	....
Sulfanilamide	144.0	65.1	26	2,420,000
p-Aminobenzoic acid	143.7	60.1	49	....
Thiourea	26.3	15.2	92	22,000
8-Hydroxyquinoline sulfate	23.9	16.6	64	....

[a] Mg. CO_2 per 100 g. dry matter per 24 hours on 10th day of trial.
[b] Mg. KOH per 100 g. wheat, dry basis.
[c] Initial germination was 94%.

Workers at the Southern Regional Research Laboratory (3, 3a, 47) have also tested the preservative action of a number of compounds by treating samples of high-moisture flaxseed with the chemicals and storing them for 6 days with constant aeration in thermos bottles. The rise in temperature and the development of free fatty acids, in comparison with a control, were measured and served as indices of the effectiveness of the various chemicals (90). Compounds which gave promise in this screening procedure were subjected to further and more prolonged tests. Ethylene chlorohydrin markedly inhibited heating and lipolysis when added in a concentration of 0.4% of the dry weight of the seed. For example, treated flaxseed with 15% moisture contained 0.4% free fatty acids after storage, whereas the untreated control sample con-

tained 17% free fatty acids. In later experiments, ethylene chlorohydrin was used as a comparative standard for evaluating other inhibitors. A list of those which were found to be equal or superior to this standard in laboratory screening tests follows:

Propylene chlorohydrin
Ethylene bromhydrin
Allyl alcohol
Beta-chloroallyl alcohol
Diethyl oxalate
Diethyl malonate
Glycol diacetate
Propylene glycol dipropionate
Propylene glycol diacetate
Vinyl propionate
Tributyl borate
Ethyl chloracetate
Ethyl chloropropionate
Methyl chloracetate
Ethyl isovalerate
Triethyl phosphite
o–Vanillin
1,3–Dimethyl–2,4–(bischloromethyl) benzene
1,3–Dimethyl–4,6–(bischloromethyl) benzene
Benzotrichloride
Chlorazene (chloramine T)
Chloramine B (sodium N-chlorobenzene sulfonamide)
Sulfanilamide
p–Toluene sulfonamide

Diethyl phosphite
Propionic acid
Beta-chloropropionic acid
Acetic acid
Butyric acid
Valeric acid
Crotonic acid
1,3–Dichloropropene–2
1,3–Dichlorobutene–2
1,3–Dichloropropene–1
Phenol
Salicyl aldehyde
p–Tertiary–amyl phenol (Pentaphen)
Sodium pentachlorophenate (Santobrite)
2–Chloro–4–phenyl phenol (Dowicide 4)
Chloro–2–phenyl phenol (Dowicide 30)
Hyamine 1622
Hyamine 10x
2–Aminothiazole
Chloroacetamide
Acrolein
Methyl vinyl ketone
Sodium cyanide

Some of these chemicals have been used in mill-scale tests with cottonseed, and Altschul (3) has reported quite favorable results. Most of these large-scale tests were made with a mixture of propylene glycol dipropionate and 1,3-dimethyl-4,6-(bischloromethyl)benzene. This mixture, applied at a rate of 10 pounds per ton to cottonseed containing 18% moisture, made it possible to store the seed for 71 days without recourse to aeration; whereas an untreated lot of the same seed had to be aerated for 30 days during the same period, thereby reducing its moisture content to 13%. Although the chemical treatment eliminated the need for aeration, the increase in free fatty acids was the same in the chemically treated seed as in that which was aerated. Other tests indicated that treatment with these chemicals assisted in maintaining the viability of high-moisture seed during storage (91).

In more recent studies (77b) the group at the Southern Regional Research Laboratory has distinguished three classes of solid organic chemicals on the basis of their selective inhibition of visible mold growth

and spontaneous heating. Thus in class I (A) they include compounds which inhibit both spontaneous heating and mold growth as follows: biphenyl, 8-hydroxyquinoline, 8-hydroxyquinoline benzoate, zinc trichlorophenate, trichlorophenyl acetate, *p*-chlorometaxylenol, 8-quinolinol phosphate, 8-quinolinol sulfate, and naphthaline. Class I (B) comprises those compounds which inhibit spontaneous heating only and include: ethyl mercury *p*-toluene sulfonanilide; tetrachloro-*p*-benzoquinone; 2,6-dichloro-1,4-naphthoquinone; 1,3,5-trimethyl-4-nitrosopyrazole; dehydroacetic acid; 1,3-dichloro-5,5-dimethyl hydantoin. Class II includes those compounds which did not inhibit heating or prevent mold growth.

Several preparations consisting largely of sodium bicarbonate and calcium carbonate have appeared on the market in the last few years, and are claimed to inhibit mold growth and heating in damp hay and grain. Thorough tests of these materials as inhibitors of heating and respiration have shown them to be worthless (117a, 120).

Commercial Feasibility of Chemical Treatment. The experiments which have thus far been conducted clearly demonstrate that certain chemicals will inhibit mold growth, lipolysis, and heating in grain. However, the eventual commercial feasibility of chemical treatment as a means of preventing the spoilage of high-moisture grain, except over rather short periods, appears to be rather doubtful. Dusting grain with fungicidal or fungistatic agents only inhibits the growth of surface molds, and damaging changes will occur over extended storage periods because of the activity of subepidermal microflora and of the seed enzymes. Gilman and Semeniuk (61) point out that the problem is further complicated by the fact that the grain may be used for biological purposes: unless the chemicals can be removed, the grain may be rendered useless for fermentation processes and feeding purposes. The discovery of a low-cost chemical which will inhibit the enzymes of the whole grain as well as those of the molds, and has no after-effect on the seed or on the usefulness of its products, is necessary before general commercial use of chemical treatment will be feasible for prolonging safe storage of high-moisture grain. Chemical control of deterioration, however, may eventually prove valuable in storing grain to be used for seed, and for inhibiting deterioration of high-moisture grain over short periods until processing or drying to safe moisture levels is undertaken. At present, drying high-moisture grain to a moisture content that is in equilibrium with an atmosphere of less than 75% relative humidity is the only safe way to prevent mold deterioration and heating.

Role of Microorganisms

In Chapter III of this monograph, reference is made to the marked

difference in the water requirements of bacteria and fungi as defined by Walter (169, 170, 171), Haines (65), and others. Thus, while a relative humidity of 75% will permit the growth of some fungi, a value of about 95% is required for the development of most bacteria. Haines pointed out that bacteria are continuously surrounded by a fluid medium, even when growing on the surface of agar, and thus depend on a respiratory exchange through a liquid medium, whereas molds have hyphae or conidia rising some distance into the surrounding atmosphere. Since the cereal grains must contain about 22% moisture to maintain a relative humidity of about 95% in the interseed atmosphere, the moisture content of grains undergoing bulk storage on the North American continent is seldom high enough to favor bacterial growth. However, bacteria are frequently involved in the deterioration of corn, and the literature concerning their role will be briefly reviewed.

Bacteria. Following the identification of *Bacillus calfactor*, by Miehe (106) in 1911, as the organism associated with the heating of hay, bacteria received considerable attention from investigators interested in the heating and spoilage of grain. Accordingly, most of the earlier studies were made at moisture contents high enough to encourage the growth of all microorganisms. James (76) and James, Rettger, and Thom (77) compared the heating powers of several bacteria and a fungus, *Aspergillus fumigatus*, on corn meal, cracked corn, and hay; the materials had moisture contents of 30% and were aerated with oxygen in Dewar flasks. The various microorganisms were found to be about equally thermogenic. Haldane and Makgill (66) cited both bacteria and fungi as primary biological agents in initiating heating. In the relatively recent studies of Carlyle (33), Norman, Richards, and Carlyle (122), and Carlyle and Norman (34, 35), emphasis was placed on the temperature requirements of microorganisms. These were classed as "mesophiles" and "thermophiles" with respective optimum temperatures of about 40°C. and 60°C. As these studies on the decomposition of plant materials were conducted at a moisture content of about 30%, a profuse variety of microorganisms was encountered. In very moist products undergoing heating, thermophilic organisms may contribute significantly to the continued respiration and heating of grain which has attained a sufficiently high temperature to kill the mold mycelia (55° to 65°C.).

Fungi. The relation between mold growth and respiratory phenomena in grain has already been discussed in several of the preceding sections dealing with various factors which influence respiration. Although molds were observed in spoiling and heating grain by many of the early investigators, the significance of the observation was obscured by the fact that the respiratory processes of molds are the same as, or are very similar to,

those of the seeds themselves. Even today, a few investigators consider that the changes which occur in moist viable grain can be explained by a marked increase in the enzymic activity of the grain with increased moisture content. Gilman and Semeniuk (61) have pointed out that this hypothesis rests, in part, on the fact that the species of molds which are found in grain are primarily saprophytes, which attack viable grain much less readily than dead organic matter. However, the large body of data obtained by numerous workers with such grains as corn, wheat, soybeans, and flaxseed supports the commonly held view that mold growth is the primary cause of the spoilage and heating of grain (38, 61, 77a, 86, 93, 100, 112, 115, 116, 117, 121, 128, 134, 138, 139, 140, 141, 155).

The belief of the earlier workers that the embryo is the seat of the major respiratory activity in grain has recently been disproven. Oxley and Jones (128) found that the respiration of wheat grains from which the embryo had been completely removed by the larvae of a moth, *Ephestia elutella* Hbn., was scarcely affected. In fact, the respiration of the embryo-free grains was very slightly higher than that of undamaged grains from the same sample; presumably this was due to invasion of the damaged kernels by microorganisms. Leach (98) has also shown that the removal of wheat embryos by means of a dental drill has little if any effect on the respiration rate. These workers conclude that the chief source of carbon dioxide in grain that is too dry to germinate is not the seed itself, since the embryo is the only grain tissue which would be expected to respire actively. On the other hand, Oxley and Jones found that removal of the pericarp of whole wheat kernels by abrasion with coarse carborundum, crushed flint, or glass powder did not interfere with the viability of the seed, but lowered the respiratory rate to about 5% of its original value. This showed that the carbon dioxide produced by wheat originated largely in the pericarp. While microscopic examination of the pericarp failed to reveal any actively developing, or living, grain structures, many samples showed an extensive mycelium on the inner surface of the epidermis. The existence of subepidermal microflora has also been noted by other workers (9, 41, 105, 118, 160).

The correctness of the view that the marked increase in the respiratory rate of grain is due to mold growth and corresponds to that moisture content which is in equilibrium with an atmospheric relative humidity of about 75% has been questioned (15). This objection is based on the fact that the acceleration in wheat respiration occurs between 14 and 15% moisture, whereas, according to Coleman and Fellows (44), wheat contains 17.5% moisture at 75% relative humidity. Actually, the

hygroscopicity data are given on a dry-matter basis, and when recalculated to the conventional "as-is" basis, the value of 17.5% becomes 14.6%. (See also Table II.)

The similarity between the shape of a respiration-time curve for moist grain and that of a microbiological growth curve has already been emphasized. It should also be noted that the behavior of natural seeds can be replicated closely by inoculating sterilized seeds with molds (Fig. 5). The low respiration at moistures below those required for mold growth is, of course, absent from sterilized seeds.

That fungi differ in their minimum water requirements for growth was clearly demonstrated in the experiments (112) with wheat which are summarized in Table I. At moisture levels between 12.3 and 14.5%, the mold count did not increase during the period of the test. *Aspergillus glaucus* began to develop at a moisture content of 14.5% and grew vigorously at 15.4 and 16.3% moisture. *Aspergillus glaucus* is among the most xerophytic of the molds, and Snow, Crichton, and Wright (149) have shown that some strains of this species will grow even at relative humidities below 75%. As the moisture content was increased above 16.8%, *A. glaucus* fell off rapidly; *A. candidus* made up more than 75% of the mold flora in the samples at 18.5 and 20.8% moisture; and at the higher moisture contents, *A. flavus* comprised more than 50% of the mold flora with *Penicillium* increasing in the range of 25 to 35% moisture. In a study of the effects of variations in moisture, temperature, and atmospheric composition on the kinds and numbers of molds, on germination, and on several biochemical properties of corn, Bottomley, Christensen, and Geddes (27) also found that the species of molds which predominated varied considerably with the conditions under which the corn was stored.

The researches of Milner, Christensen, and Geddes (112) indicate that the relation of the respiratory quotient to the moisture content of the grain is a complex one. At a moisture value below that necessary for molds to grow (12.3 to 13.8% moisture), the respiratory quotient of wheat increased from about 0.5 to 0.8 as the moisture increased, and there was no significant change in the respiratory quotient with time. At 14.5% moisture, in the critical range for the initiation of mold growth, the respiratory quotient remained essentially at 0.9 throughout the trial. At 15.4% moisture, where molds became well established, a value of 0.9 was maintained for the first 9 days of a respiratory trial, but dropped to 0.8 in the latter days of the trial. This characteristic was common in the moisture range between 15 and 19%. At more elevated moisture levels, approaching the germination requirement, the respiratory quotient tended to remain at 1.0. With soybeans, it was found

that an increase in moisture content was accompanied by a rise in the equilibrium respiratory quotient from 0.6 for dry seeds (below the critical value) to a value of 1.0 in damp seeds where mold respiration was predominant.

Evidence regarding the role of fungi in grain respiration has been obtained by several workers with such grains as corn, wheat, flaxseed, and soybeans. Whether molds are similarly involved in the deterioration of moist cottonseed has been questioned, although the seed is known to bear a fairly rich internal flora of parasitic and saprophytic molds (9). Malowan (101) found that the respiration of moist cottonseed was not decreased when the seed was treated with copper sulfate or mercuric chloride, and this led him to conclude that microorganisms were not a factor in the respiration of this seed. More recently, Altschul and his associates (2, 80, 81) at the Southern Regional Research Laboratory have expressed some doubt whether molds are involved in the deterioration of moist stored cottonseed. They favor the view that the major lipolytic, respiratory, and heating activities of cottonseed in storage are due to the enzymes of the seeds themselves, and that microbiological activity is, at best, a secondary factor which only comes into play after deterioration has progressed to the point where the viability of the seeds has decreased. Reduced viability probably renders the seeds increasingly susceptible to infection, and the microorganisms may ultimately become the predominant factor in the deterioration process. This view is based on their observation that treatment with certain chemicals which inhibited lipolysis did not necessarily inhibit respiration; if microorganisms were the cause of these processes, the inhibition of their growth should affect both in a similar manner. However, mold counts were not made, and there was no experimental basis for assuming that the seed treatments which were employed had inhibited mold growth. Recently, Christensen, Olafson, and Geddes (41) found that compounds of even rather high toxicity to molds were relatively ineffective in protecting moist cottonseed from invasion by storage molds. Because of the peculiar structure of the seed coat, molds can gain easy access to the interior of the moist seeds where they can grow vigorously and sporulate profusely without betraying their presence by any external evidence. The results of this study clearly showed that increases in mold population were accompanied by increases in the production of carbon dioxide, fatty acids, and heat, as has been found with other kinds of seeds.

Evidence that the increase in fat acidity that occurs when various kinds of grain are stored at high moistures is due mainly to the action of mold lipases, rather than to activation of the seed lipases, has been

obtained by investigators at the Minnesota Agricultural Experiment Station (27, 61a, 111, 112, 113, 114, 115, 116, 117, 134). Typical results are shown in Table I on page 164. When high-moisture grain was stored under nitrogen, practically no mold growth occurred, and there was a negligible increase in fat acidity over the period of the trials. As the aeration was increased, there was a concomitant increase in the mold population and in fat acidity. That molds may produce lipase in quantity has been shown by Eyre (53), Kirsh (84), Thibodeau and Macy (161), Nagel and Semeniuk (121), and others. The researches of Nagel and Semeniuk are of particular interest in relation to the origin of the increase in fat acidity in high-moisture grain when stored. These workers grew pure cultures of nine fungi (which had been isolated from naturally molded corn) on steam-sterilized corn containing about 32% moisture and found that all the fungi increased the fat acidity of the corn. The greatest increases were produced by *Penicillium chrysogenum I, P. chrysogenum II, Aspergillus niger, A. flavus, Mucor racemosus,* and *A. amstelodami.*

Precise and conclusive evidence of the relative importance of seed metabolism and that of microorganisms in grain deterioration can only be obtained by separating their activities and evaluating them individually. This would involve studies with sterile viable seeds produced by treatments which kill microorganisms or completely inhibit their growth. It would be difficult to produce sterile seeds and to keep them free from molds.* † Moreover, the results obtained in respiration or other trials with seeds treated to kill or inhibit molds are open to the criticism that the metabolic activities of the grain itself may be affected.

Milner, Christensen, and Geddes (113) found thiourea to be an effective mold inhibitor of low toxicity to wheat, and they used this chemical at the rate of 1.0% of the grain in an attempt to estimate the inherent respiration of wheat at moisture contents up to that required

* Promising technics have recently been developed in England. Wheat free from subepidermal mycelium has been produced by enclosing the heads of growing plants in round-bottom flasks in which the relative humidity is kept below 50% with small bags of silica gel. Heads are enclosed when the grain has reached full size and its moisture content has dropped to 60 to 70%. Cobalt thiocyanate paper is used to indicate when silica gel bags should be replaced. On hot days, when atmospheric humidity is below 40%, flasks are removed and replaced by perforated cellophane bags to avoid the excessive temperature which might otherwise develop within the flask. Spraying of growing heads at 3- to 4-day intervals with 8-hydroxyquinoline sulfate, applied at a concentration of 1% in a 0.5% aqueous solution of a wetting agent, Triton X-100, has also been found effective. Internal mycelia are sometimes present but appear to be dead since no mycelia develop from cultures of surface-sterilized grain. (Personal communication from Mary B. Hyde, Pest Infestation Laboratory, Department of Scientific and Industrial Research, Slough, England.)

† Since this chapter was written, workers at the University of Minnesota located a white wheat grown under irrigation in Montana which was free from internal molds. Surface disinfection of this sample made it possible to compare the respiration of the grain itself with that of the same grain to which molds obtained from other wheat were added. The respiration of the mold-free wheat at 35°C. and several moisture levels between 20 and 31% was low and almost constant with time; in contrast, the respiration of the moldy wheat markedly increased after a few days. At the end of the 19-day respiration trials, the free fatty acid values for the moldy samples had increased about eightfold while those of the nonmoldy samples were comparable with those of the wheat before storage.

TABLE VI

INFLUENCE OF MOISTURE CONTENT AND THIOUREA TREATMENT ON RESPIRATORY RATE, MOLD GROWTH, FAT ACIDITY, AND VIABILITY OF WHEAT (From Milner, Christensen, and Geddes, 112)

Samples analyzed after completion of 10-day respiration trials at 30°C.

Moisture	Respiratory Rate[a]		Mold Colonies per g.		Fat Acidity[b]		Viability[c]	
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
%							%	%
14.2	0.16	0.17	5,500	5,766	14.0	18.7	96	97
16.1	2.23	0.94	5,500	4,933	15.9	20.2	94	95
17.9	100.5	6.9	10,166	5,000	50.1	14.1	26	94
21.3	461.2	42.8	5,310,000	23,700	141.2	20.4	11	93
24.3	1,512.8	90.6	6,710,000	34,800	92.4	38.5	5	81
26.9	1,375.4	184.4	2,580,000	10,660	87.0	21.3	8	19
30.3	2,539.4	209.6	65,000,000	77,500	231.4	55.9	..	15
33.0	2,267.4	291.8	88,000,000	5,575	222.3	19.2	..	10
35.5	3,394.7	592.6	95,000,000	50,000	265.2	58.0	..	2

[a] Mg. CO_2 per 100 g. dry matter per 24 hours on 10th day of trial.
[b] Mg. KOH per 100 g. wheat, dry basis.
[c] Initial viability was 94%.

for germination. The comparative respiratory rates, mold count, germination, and fat acidity values, for treated and untreated wheat, after storage at 30°C. for 10 days at various moisture levels are given in Table VI. Although thiourea treatment did not entirely prevent mold development with wheat held at moisture contents above 17.9%, mold growth was greatly inhibited and respiration and fat acidity were markedly lower than those of the untreated grain, especially at moisture levels above 17.9%. The treated grain maintained higher viability than the untreated grain; moreover, since there was little decrease in the viability of the former when stored at moisture contents up to 24.3%, there was apparently little interference with normal seed metabolism as a result of the treatment. The markedly lower respiratory rates and lower fat acidities of the treated samples stored at moisture contents of from 14.2 to 24.3% are apparently due mainly to the metabolism of the seed, which also increases with moisture content. This respiration is of a low order and does not exhibit the sharp upward trend at the critical moisture value which occurs when mold growth is uninhibited. At moisture values above 17.9%, however, some mold growth occurred in spite of the presence of the inhibitor.

Role of Insects

When grain is infested with insects, they contribute to the over-all respiration. Even though insects never represent more than a very small fraction of the total mass, their metabolism is so high in proportion to that of the dormant grain that their contribution to the total respiration may be very great. This has been very strikingly exemplified by Oxley (126) who cited a typical wheat sample infested with 10 weevils (weighing only 25 mg.) per pound of grain. The total carbon dioxide production of the insects was about seven times that of the wheat, so that the insects were producing about 130,000 times as much carbon dioxide as an equal weight of grain. Indeed, Howe and Oxley (75) have pointed out that the carbon dioxide production of grain may be used as a convenient estimate of infestation, and they have described a simple technic for this purpose.

Several investigators have studied the respiration of insects and have suggested that their high metabolic activity may be a prominent factor in the heating and spoilage of grain (11, 99, 119, 136, 157, 158). Lindgren (99) investigated the effect of moisture and temperature on the respiration of rice and granary weevils in wheat and obtained the results shown in Table VII. Both species have certain optimal moisture requirements; if there is insufficient moisture present, the metabolic rate decreases and the insects may die. The metabolic activity was higher at

TABLE VII

INFLUENCE OF MOISTURE CONTENT AND TEMPERATURE ON THE RESPIRATION OF RICE AND GRANARY WEEVILS IN WHEAT (From Lindgren, 99)

Wheat Moisture	Carbon Dioxide Production in 24 Hours					
	Wheat Respiration per 100 g.		Respiration per Gram of Weevils			
			Sitophilus oryzae[a]		*Sitophilus granaris*[b]	
	25°C.	35°C.	25°C.	35°C.	25°C.	35°C.
%	*mg.*	*mg.*	*mg.*	*mg.*	*mg.*	*mg.*
8.7	trace	trace	75.8	64.5	119.3	114.5
10.7	trace	0.2	150.0	107.7	117.4	212.9
14.0	0.7	1.4	206.4	261.3	169.7	244.9
15.2	1.0	2.2	201.9	289.4	170.8	248.2
17.4	13.2	21.2	204.8	232.0	190.8	225.1

[a] At 8.7% moisture, 35.2% and 100% of the rice weevils were dead at 25°C. and 35°C., respectively; at 10.7% moisture the corresponding figures were 3.6% and 77.6%.

[b] At 8.7% moisture, 0.5% and 48.8% of the granary weevils were dead at 25°C. and 35°C., respectively.

35°C. than at 25°C. On wheat at 8.7% moisture, a larger percentage of the insects died at the higher temperature. Lindgren pointed out that the metabolic water and heat given off by insects hasten the deterioration of grain in storage and may even initiate it. If carbohydrates are the nutrients metabolized by the insects, the carbon dioxide values show that 70 granary (approximately 0.148 g.) or 100 rice weevils (approximately 0.136 g.) would produce about 1.0 g. of moisture in 100 days at 25°C. or in 80 days at 35°C.; accordingly, the moisture content of wheat stored at approximately 14% may be increased above the critical range in a relatively short time. Howe (74) and Oxley and Howe (127), on the other hand, have discounted the view that water produced by the metabolism of the grain, molds, and insects plays any large part in increasing the moisture content of grain in bulk storage. A developing insect infestation produces a rise in temperature, and water evaporates from the grain until the equilibrium relative humidity is restored. The warmer and moister air has a lower density than the cooler air surrounding the infested areas, and convection currents are set up which translocate moisture from the hotter to the colder regions of the mass of grain.

It has been proposed by Oxley (126) that clear-cut differentiation can be made between what he terms "dry grain heating" due to insects and "damp grain heating" which is presumably caused by developing

fungi. The former is due to insect respiration and generally occurs in wheat at moisture levels below 15%. Temperature may reach a maximum of 37.8°–42.2°C. (100°–108°F.). Damp grain heating, on the other hand, predominates at moisture levels above 15%, and may reach temperatures as high as 55°C. (131°F.) in grain bulks of sufficient size to provide adequate insulation. Oxley believes that the temperature attained in a grain bulk, whether it be due to insects or other external causes, is the deciding factor in the initiation of progressive heating. Thus he conceives of a critical temperature rather than a critical moisture content as initiating spontaneous heating.

The writers believe that the weight of the evidence reviewed in this chapter indicates that heating is probably initiated at any temperature at which fungi will grow, and that the heating noted in grain caused by moisture values beyond the critical level is largely the cumulative result of fungal respiration in the grain bulk.

Biochemical Changes in Stored Seeds Associated with Respiration

Although the physical and chemical changes occurring in stored grain are the subject of another chapter in this volume, the fact that certain biochemical alterations are so intimately related to respiratory mechanisms necessitates a brief treatment of such changes here.

Carbohydrates appear to be the first seed constituents utilized in the respiratory processes in stored grain. This results in an apparent increase in the fat and protein content. Ramstad and Geddes (134) have shown that a marked increase in reducing sugars occurs in soybeans containing more than 15% moisture, with an equally marked decrease in the nonreducing sugars and in the iodine value of the seed oil.

The relationships of moisture content to respiratory activity as well as to the changes in fat acidity, sugars, and germination, which occur in stored wheat, are indicated in Table I. The total sugars decreased as the moisture content of the grain undergoing storage was increased beyond 15.4%, but the reducing sugars showed little or no increase until the moisture content reached 20.8%.

The direct relations between the respiratory activity of grain, fat acidity, and general deterioration, shown in Tables I, IV, V, and VI, have been noted by many workers, and fat acidity has been regarded as a very sensitive index of incipient grain deterioration (176, 177, 178). As has already been pointed out, there is considerable evidence to indicate that the increase in fat acidity at high storage moistures is due mainly to the action of mold lipases. Repression of mold growth by limiting the oxygen supply or by the use of fungistatic agents results

in lower fat acidities (Table V). However, in a recent study, Bottomley, Christensen, and Geddes (27) obtained a correlation of only 0.20 between mold count and fat acidity, and the quantity of nonreducing sugars present in the grain proved to be a better index of its condition. These results may be due to the failure of mold counts to provide a reliable index of mold activity. The species of molds which predominated at the end of the 12-day storage period varied considerably with the conditions under which the grain was stored. Different species of molds are known to differ greatly in the amounts of lipase and other enzymes which they produce and in their ability to metabolize such products as fatty acids and maltose (53, 61a, 84, 121, 166, 167). Samples of grain stored over various periods of time under conditions which favor the growth of different species of molds would hardly be expected to show a close association between fat acidity and the soundness of the grain. Further research may well reveal that fat acidity is of less value as an index of grain deterioration than has been commonly supposed.

Factors Influencing Seed Viability

Several investigators have shown that the viability of seeds decreases with increasing moisture content and with the time and temperature of storage (21, 31, 40, 50, 100, 134, 135, 144, 145, 163, 174). Oathout (123) noted a decrease in the viability of soybeans when they were stored at moisture contents exceeding 14%, particularly when the beans were damaged in threshing and molds were thus able to attack. Low temperatures largely prevented loss in vitality of moist beans. Wilson (174) believed that injuries to the outer seed coats give fungi access to the nutrients within the endosperm, and that the resultant decreased viability arises from the direct competition between the molds and the embryo of the weakened seed. Mead (105) drew attention to the fact that fungi may develop from cereal seeds sown on agar, after treatment with organic mercury dusts or formalin. The growths were believed to arise from deep-seated infections rather than from surface-borne microorganisms, as the latter were presumed to have been effectively destroyed by the fungicides. Robertson, Lute, and Gardner (135) found that wheat, oats, and barley, which had been treated with an organic mercurial and stored at high humidities, showed greater loss of viability than untreated seeds; this increased loss of viability became particularly pronounced at relative humidities exceeding about 74%. Although the greatest loss in viability of seeds is associated with moisture contents favoring mold growth, there is a definite and progressive effect at lower moistures, particularly at elevated temperatures of storage (21, 134). Other workers have confirmed the toxic effects on seeds of long

exposure to mercurial fungicides. These fungicides may decrease viability without destroying molds living well within the seed.

That certain species of fungi decrease seed viability through some toxic principle they elaborate has been shown by Thomas (163) and Tervet (160). Thomas made germination tests on wheat after treating the seed with filtrates of pure cultures of 13 species and strains of molds which are commonly found on grain. While all the filtrates somewhat lowered the germination, *Aspergillus flavus* had a very pronounced effect. Working with soybeans, Tervet (160) found that an increase in the moisture content and time of storage at room temperature resulted in an increase in the number of mold-infected seeds, a decrease in the germination, and a greater benefit from seed treatment with a fungicide. Upon studying the influence of 14 mold species on viability, he found that the spores of only one of these, *Aspergillus flavus,* influenced the germination; its deleterious effect could be counteracted by dusting the seeds with fungicides before planting. Treatment of seeds with cell-free filtrates of three species of molds, *Aspergillus flavus, A. niger,* and *A. ochraceus,* lowered the germination. It may be concluded that molds play a prominent role in promoting losses in the vitality of seeds stored at moisture contents favorable to their growth, especially when the seed coats have been damaged.

The low respiration exhibited by viable dormant seeds at low moisture levels, coupled with the fact that any storage conditions which reduce respiratory activity (e.g., low moisture, low temperature, reduced oxygen supply) tend to prolong seed viability, raises the question of whether respiration is vital to the maintenance of life in the dormant seed. However, it is reasonable to postulate that the continued life of the seed depends upon the utilization of some labile organic matter present in the embryo (126). The length of time the seed remains viable in storage may be directly proportional to the amount of this unknown material initially present, and to the rate at which it is subsequently utilized. Any process, such as respiration, which tends to speed up the dissipation of this material might then be assumed to reduce the life expectancy of the seed.

A recent critical review of the literature on factors which influence the storage life of seeds (49) suggests that the intermediate metabolic products, accumulating as a result of anaerobic respiration, may be toxic to the seed. The evidence is strong that the decrease in the vitality of stored seeds is related to a degeneration in the cell nuclei of the embryo, and that very similar degeneration may be caused by aging, heating, and x-ray treatment of dried seeds.

Under certain conditions, the respiration of the seed bears no rela-

tionship to its viability; for the activity of many enzymes continues and may even be stimulated in seeds which have lost the integrated biochemical organization necessary for life. Such conditions exist in grain which has been killed by frost, toxic gases, pathogenic organisms, or insects. Altschul (2) speculates that the rate of storage deterioration in seeds may be related to an invisible form of deterioration which affects the normal dormancy of seed enzymes. Crocker (49), on the other hand, believes that very few enzymes exist as such in dormant seeds. He suggests that these biochemical catalysts are synthesized as required in the protoplasmic constituents when germination starts. It appears probable, nevertheless, that viability in dormant seeds is intimately dependent on at least a few potentially active and highly integrated enzyme systems. That the loss of viability in seeds may in some cases be related to the inactivation of certain anaerobic dehydrogenase enzymes has been indicated recently by extensive studies of seed viability made with oxygen-sensitive dyes such as triphenyltetrazolium chloride (48, 104, 132).

Germ-Damaged or "Sick" Wheat

Among the most poorly defined types of damage in wheat associated with storage deterioration is the condition known to the grain trade as "sick" wheat. This condition is manifested by kernels showing a dull appearance; the germs are dead and exhibit various degrees of darkening. The dark color of the embryo is the primary commercial criterion of "sick" wheat. Mold growth is usually present on commercial samples of such grain, and the fat acidity is high.

The cause of "sick" wheat as distinct from causes of other forms of damage of high-moisture wheat in storage, such as heating, is not definitely known. The condition seems to develop principally in wheat stored in large quantities, and makes its appearance only after a considerable time. However, it is sometimes found in freshly harvested wheat when delivered to elevators for storage. Its occurrence may be associated with conditions favoring germination followed by conditions which kill the germ.

Swanson (155) found that germ damage would develop in wheat when the samples were stored for a sufficient length of time, even though mold growth was inhibited by the exclusion of air from the containers or by treatment of the seeds with Ceresan (ethyl mercury phosphate). Thomas (163), on the other hand, showed that toxic principles are elaborated by molds, principally the species *Aspergillus flavus*. The proportion of "sick" kernels, as evidenced by visual examination, increased with increasing moisture content of the grain as well as with increasing temperature and length of storage. Thus, wheat containing 12.2% moisture

stored at 40°C. developed "sick-wheat" symptoms when stored 279 days or longer, but not when stored at a lower temperature. A small percentage of "sick" kernels was produced in 32 days when wheat containing 18.6% moisture was stored at 5°C., whereas 100% "sick" kernels were found when wheat at this moisture content was stored at higher temperatures or for longer periods. In general, an increase in the percentage of kernels which were classified as "sick" was accompanied by an increase in fat acidity and a decrease in germination.

Carter and Young (37) and Coleman, whom they cited, have suggested that the "sick-wheat" condition may be produced by a lowering of the oxygen pressure in the interseed air. This causes a slowly developing fermentation which results in by-products toxic to the embryo. While they discarded all samples which showed visible mold growth in their experiments, they emphasize that deterioration as a result of fungal action should not be overlooked since mold damage can occur before it is possible to detect mold growth with the naked eye (41, 95, 160).

Milner, Christensen, and Geddes (111) examined the various types of microflora which occur on commercial samples of "sick" wheat. They also studied the influence of temperature, moisture, time, and storage atmosphere on the development of "sick" wheat in the laboratory. Germ-damaged kernels hand-picked by Federal grain inspectors from commercial lots of wheat were principally infected with *A. glaucus* and *Penicillium* sp. and to a lesser extent with *A. candidus, A. flavus,* and *A. niger.* In contrast, sound wheat samples from the same lots were largely contaminated with *Alternaria* which disappeared when storage conditions favored the proliferation of the *Aspergilli.* When sound wheat was inoculated with various molds and bacteria, isolated from "sick" wheat, and stored in air, it lost viability faster than did the controls, and most of the nonviable seeds had symptoms typical of "sick" wheat. "Sick" kernels were produced by storing wheat containing 18% moisture under atmospheres of carbon dioxide, nitrogen, or oxygen in sealed containers. Only under oxygen did molds proliferate, whereas "sick" kernels appeared under all atmospheres.

Fat acidity increased in all samples stored at 18% moisture, but the increase was greatest in those held under oxygen. The "sick-wheat" condition, therefore, was not entirely due to molds, but their metabolic activity increased it. Of the various mill fractions of "sick" wheat, the low-grade flour gave the highest fat acidity value, whereas with normal wheat, the bran was highest in this factor. This suggests that the lipolytic agencies in "sick" wheat do not occur primarily in the bran or germ but more probably in the aleurone and scutellar tissues, the tissues credited with enzymic functions which become highly active on

germination of the seed.

The available evidence shows that the development of "sick" wheat can occur under anaerobic storage conditions. The deteriorative effects of molds increase its formation. It is unlikely that bacteria are an important contributory factor since they grow only at moisture contents equivalent to a relative humidity of about 95%. Any condition which tends to increase the respiratory rate of the grain in storage favors germ damage. The increased enzymic activity may lead initially to a weakening of the germinative powers of the seed and eventually to rather extensive chemical deterioration. In further studies of this phenomenon, the nature and distribution of various enzyme systems, such as lipases and oxidases, as well as the moisture relationship which governs their activity, should be investigated. The possibility that nonenzymic browning may be a factor in the discoloration of the germ should not be ignored.

At the time when this chapter was written, an opinion was prevalent in the grain trade that "sick" wheat was an infectious condition, and that the "sickness" could therefore be transmitted to sound wheat. Another opinion held that "sick" wheat arises as a result of the frustrated attempt by wheat to germinate in an atmosphere containing insufficient oxygen (25, 26).

Heating of Stored Grains

The term spontaneous heating has long been used to denote the increase in temperature, frequently observed in stored grain or other agricultural materials, which may occur without any external cause. The heating is a direct result of the respiratory activity of the various biological agencies which are operative in such materials. It usually commences in localized areas of high-moisture content. Grain has a low specific heat, and if heat is produced more rapidly than it is dissipated by thermal conduction through the grain, by radiation, by conduction and convection in the interseed air, and by evaporation of water, the temperature of the grain rises. The rise in temperature increases the rate of respiration so that a continually self-accelerating process takes place. Damage from bin burning will occur if the temperature of the grain is allowed to become higher than about 43°C. Grain stored at moisture contents below those in equilibrium with an interseed atmosphere of about 75% relative humidity is not subject to heating over normal storage periods, unless it is infested with insects. The respiratory activity of the dry, insect-free grain is so low that the small amount of heat produced is normally dissipated without a significant increase in temperature. However, when the moisture content of the grain is suf-

ficiently high to permit mold growth, the total respiratory activity and heat production may be so great that increases in temperature occur. In bulk grain, molds and insects are the principal contributors to "spontaneous" heating. In hay and silage, where the moisture contents are high enough to permit bacterial growth, bacteria may also contribute to the heating (35).

Methods of Measurement. When high-moisture grain is stored in bulk, heating may take place which would not occur in a small sample of the same lot of grain. This is a result of the so-called "mass effect"; grain is a relatively poor heat conductor and since the loss of heat is proportional to the surface, the loss is reduced when the mass is increased. Various workers have made laboratory studies of heat production in small lots of grain by using insulated boxes (43) and silvered Dewar flasks (90, 176), but even the insulation provided by the latter leaves much to be desired (130).

In recent years, several investigators have constructed apparatus by which the spontaneous heating of small samples of grain could be studied under conditions which are nearly adiabatic. The adiabatic respirometer originated by Working (175) has been used to study the heating of soybeans, flaxseed, and sunflowerseed (134, 138, 139). Milner and Geddes (117) and Schricker (139) improved the apparatus by providing more precise temperature regulation, more accurate control of aeration of the heating grain, and better means for following respiration. The improved form of apparatus has been used to investigate the adiabatic

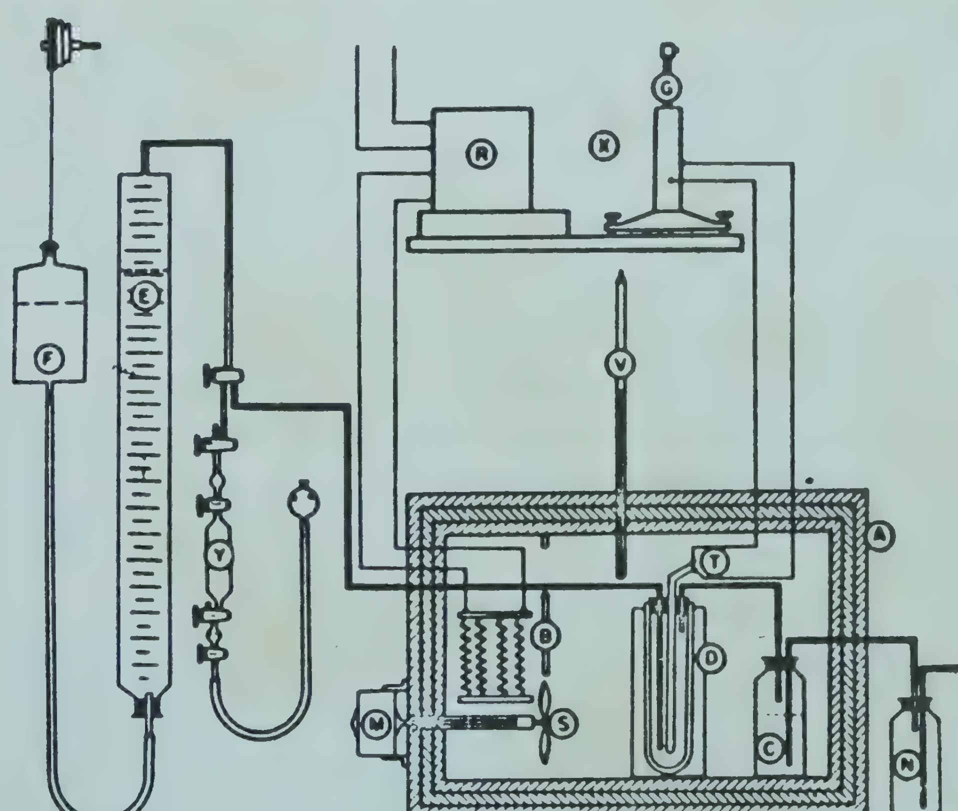

Fig. 8. Diagram of apparatus used to study the spontaneous heating and respiration of seeds (from Milner and Geddes, 117).

heating of soybeans, wheat, flaxseed, and cottonseed (41, 112, 117, 139).

The apparatus used by Milner and Geddes is illustrated in Figure 8. The insulated air bath *A* consisted of a wooden thermostat covered with two layers of Celotex. Dewar flask *D*, which may be one quart, one pint, or half-pint in size, contains the seeds whose heating characteristics are to be studied. Copper-constantan thermopile *T* has 24 junctions, 12 in the seed sample and 12 exposed on the outside of the Dewar flask to the air of the bath. Slight heating of the seeds in *D*, causing a temperature differential between the two ends of the thermopile, results in a flow of electric current through the coil of a sensitive D'Arsonval galvanometer *G*. A mirror, attached to the galvanometer, rotates a reflected light beam from a fixed integral light source along path *X* to a photoelectric cell actuating a relay in box *R*, which controls the heater coils in the air bath. The air in the thermostat is circulated continuously over the heaters by fan *S* and motor *M* through holes in the baffle *B*. When the air temperature of the bath reaches that of the seeds in the Dewar flask, the current in the thermopile circuit falls to zero and the torsion of the galvanometer coil suspension causes the light beam to recede from the photocell, thus interrupting the current to the heaters. The temperature of the air bath is thus kept continuously in step with that of the seeds in the Dewar flask, which are thus allowed to heat under virtually adiabatic conditions.

A continuous curve of seed heating may be obtained over periods of days or weeks by simply reading the thermometer *V* inserted in the air bath at regular intervals. Not shown in the diagram is an auxiliary heater, controlled by an external rheostat, which is used to compensate for heat losses from the system as the temperature of the apparatus rises. In practice, the apparatus is initially calibrated by placing warm water (45°–60°C.) in the Dewar flask and adjusting the galvanometer suspension torsion until the bath actually cools about 0.2°C. in 24 hours. Conditions are thus not strictly adiabatic, but any possibility of the seeds being heated by the system is thereby avoided. At the end of a heating trial with seeds, the apparatus is again checked with warm water in the same manner. Aeration of the seeds in the Dewar flask is accomplished by the system used by Milner and Geddes (115) in their studies on soybean respiration at constant temperature.

To obtain information on chemical and microfloral changes in the heating seeds as a heating trial progressed, a number of small bottles (not shown in the sketch) containing subsamples of the seed used in the Dewar flask were placed in the air bath and aerated by means of an independent siphon bottle system. By this procedure, control of the temperature in the air bath was accomplished by the seeds heating in

the Dewar flask, while small samples of the same grain, subjected to the same temperature changes, could be removed periodically for chemical and microfloral examination. In later studies with wheat (112), further improvements in the operation of the apparatus were effected by replacing the galvanometer-photoelectric relay arrangement with a sensitive electronic continuous balance potentiometer,* which allowed for reliable adiabatic control within narrower limits.

The Course of Spontaneous Heating. The heating of various agricultural commodities, particularly damp hay, has been a subject of research for many years, and several excellent reviews of the factors which are involved have been published (29, 30, 71, 72, 77).

One of the earliest controlled studies of heating due to biological agencies was that of Cohn in 1890 (43). He showed that moist germinating barley, maintained in an insulated box, could reach a temperature of 40°C. at which the plants were killed. This was followed by a secondary rise in temperature to 65°C., which he attributed to thermophilic organisms, principally *Aspergillus fumigatus.* Heating ceased when oxygen was excluded.

Darsie, Elliott, and Pierce (50) carried out similar studies in Dewar flasks and pointed out that temperature increases due to the respiration of germinating seeds were slight compared to those caused by mold growth. Gilman and Barron (60) confirmed these observations and concluded that these facts strongly suggest the probability that, in bins of stored grain, marked increases in temperature may be ascribed to mold growth.

Many other investigators have studied the thermogenic activity of microflora growing on a variety of moist agricultural materials (18, 19, 33, 34, 35, 68, 76, 77, 122, 172), and several have speculated on the relation of microfloral heating to spontaneous combustion in biological materials (29, 30, 68, 71, 72). The results of these investigations cannot be related directly to the heating of grain in bulk storage because the samples usually contained about 30% moisture, which is considerably higher than that normally encountered in stored grain. At such high moisture values various types of molds, yeasts, and bacteria could proliferate, whereas only those species of molds that can grow at relatively low humidities are normally of importance in the respiration and heating of stored grain. These studies have indicated that two stages of heating are caused by microflora. The first stage, attributed to the metabolic and respiratory activity of mesophilic nonspore forms, including molds, ends at about 50° to 55°C., while a secondary heating to a maximum of 70°C. is due to thermophilic bacteria. This maximum, which is about

* Brown "Electronik" potentiometer. For a description of this instrument see Slater (146).

the thermal death point of most vegetating microorganisms, is some 160°C. lower than that necessary for the ignition of hay. Many investigators have therefore concerned themselves with the problem of explaining the great increase in temperature between the death point of the thermogenic microorganisms and that required for spontaneous ignition (30).

In 1911, Miehe (106) pointed out that the initial heating of damp hay to 70°C. is due to microorganisms and suggested that continued heating above this temperature is possibly due to chemical changes brought about by the dry distillation of carbohydrates with the formation of a pyrophoric substance which would oxidize spontaneously. Haldane and Makgill (66) have shown that purely chemical auto-oxidation and heating may take place at temperatures as low as 38° to 41°C., at which biological heating is very active. By holding moist hay at temperatures just beyond the thermal death point of microorganisms, they noted that chemical oxidation is characterized by respiratory quotients of less than unity; in contrast, biological oxidation yielded a respiratory quotient of unity or more. Hoffman (71, 72) also found that the R.Q. of hay held at 77° to 80°C. was low and concluded that chemical oxidation is more marked beyond the temperature range usually ascribed to the activity of microorganisms. He writes, "Heat from external sources, exclusive of heat from bacterial action, produces some change in the constituents of alfalfa that render it more susceptible to oxidation." Groenveld and Knaup (63) showed that pyrophors could be produced by heating soybean meal to 110°C. by which treatment the moisture fell to 1.6%. On subsequent exposure to air, the temperature of the meal rose rapidly to 280°C. and ignition occurred in 2 hours.

In recent years, several heating trials under nearly adiabatic conditions have been conducted on small samples of grain stored at moisture contents well below those required for active germination or for bacterial growth, but within the limits frequently encountered in commercial bulk storage. Employing aeration, Ramstad and Geddes (134) succeeded in obtaining a maximum temperature of 88.5°C. with naturally damp soybeans (24.5% moisture) by the end of a 26-day experiment. Sallans, Sinclair, and Larmour (138) conducted similar adiabatic trials with flaxseed and sunflowerseed. They obtained sharply increasing rates of temperature rise with moisture increases above the minimum levels at which heating would occur. Storage periods of less than two months produced heating in flaxseed at 11.4% moisture and in sunflowerseed at 10.5% moisture; it therefore appeared that the commercial Canadian limits of 10.5 and 9.5% moisture respectively are not too low for these grains. An acceleration in the over-all respiration rate of these grains

TABLE VIII

INFLUENCE OF SPONTANEOUS HEATING ON CHEMICAL COMPOSITION, MOLD INFECTION, AND GERMINATION OF SOYBEANS CONTAINING 22.8% MOISTURE (From Milner and Geddes, 117)

		Chemical Analyses								
				Sugars						
Days	Temp.	Crude Protein (N x 6.25) Dry Basis	Non-protein Nitrogen	Total[a]	Non-reducing as Sucrose	Reducing as Glucose	Reducing as % of Total	Crude Ether Extract (dry basis)	Seeds Infected With Fungi[b]	Germination
	°C.	%	*mg./10 g.*	*mg./10 g.*	*mg./10 g.*	*mg./10 g.*	%	%	%	%
0	24.4	35.4	22.4	444	400	44	10.0	21.6	3	93
3	29.4	35.4	21.2	410	378	32	7.8	19.5	11	73
5	37.1	35.8	21.2	405	373	32	6.9	20.2	16	52
7	44.4	35.1	22.2	378	347	31	8.1	20.2	27	30
8	49.3	35.2	23.6	433	382	51	11.8	20.3	64	0
10	53.7	35.4	28.2	417	334	83	19.9	19.4	40	0
12	55.1	35.7	34.7	491	245	246	50.1	15.3	14	0
13	55.2	35.8	32.4	438	251	187	42.6	14.9	13	0
15	59.7	36.1	32.3	443	226	217	48.9	13.6	9	0
17	67.3	36.3	35.7	432	172	260	60.3	12.0	0	0
19	77.0	36.6	35.0	291	27	264	90.8	10.5	0	0

[a] Sum of sucrose and glucose.
[b] The majority of the fungi were Aspergillus spp.

preceded heating, and final maximum temperatures of 51° to 52°C. were recorded. The authors conclude that normal embryonic activity is insufficient to cause heating and that the growth of microflora is responsible.

Milner and Geddes (117) made simultaneous measurements of the viability, mold count, chemical changes, respiratory exchange, and temperature increase in aerated soybeans containing 22.8% moisture (equilibrium relative humidity approximately 92%) under approximately adiabatic conditions. The results summarized in Table VIII and Figure 9 clearly show that two distinct ranges of temperature increase occurred. The first heating stage, which is a consequence of the metabolism primarily of the molds, ends when the thermal death range (50°–55°C.) of these biological agencies is reached. The species *Aspergillus glaucus* and *A. flavus* were predominant. The second heating stage, concealed in its lower range under natural conditions by the upper temperature range achieved by the molds, appeared at temperatures higher than those at which the seeds and molds were killed.

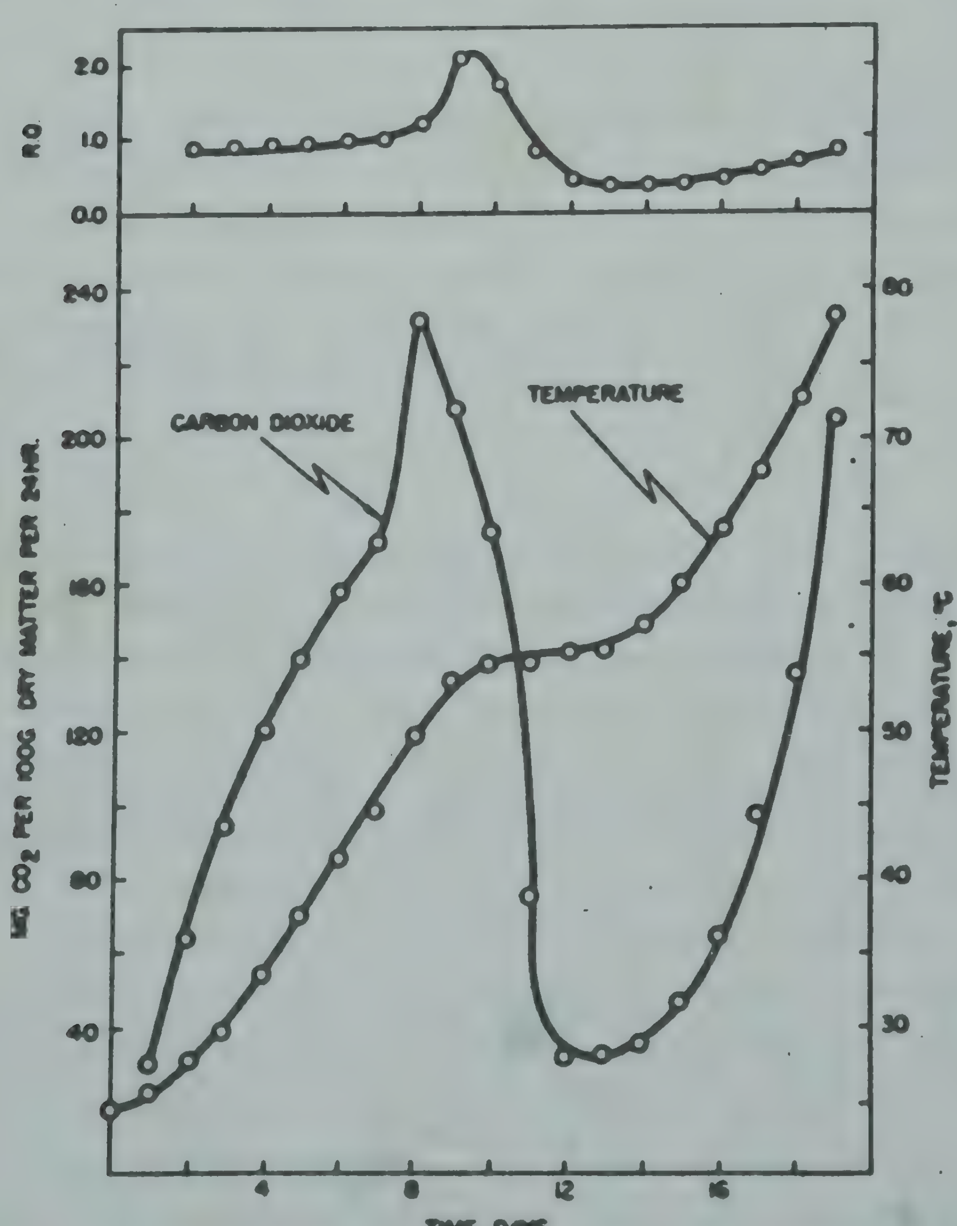

Fig. 9. The course of spontaneous adiabatic heating, respiration, and respiratory quotient, exhibited by Illini soybeans, under adiabatic conditions, at 22.8% moisture. The aeration was doubled on the seventh day. (From Milner and Geddes, 117.)

As these workers showed that autoclave-sterilized seeds would heat spontaneously when stored at about 54°C. (or higher) under adiabatic conditions if adequately aerated, this secondary heating phase must be ascribed to nonbiological oxidation. Milthorpe and Robertson (119) have estimated that about 2.5% of the carbon dioxide output from wheat is due to this chemical oxidative process at 40°C., 25% at 60°C., and that all the carbon dioxide evolved above 70°C. is due to this phenomenon. The experience of the authors suggests that the first two ratios are somewhat low. With sufficient aeration under controlled laboratory conditions, spontaneous heating following the attainment of 54°C. apparently has no upper limit short of ignition temperature; in one experiment, the temperature increased 11.5°C. in 24 hours to 101°C. when the experiment was terminated (115). Heating studies conducted by inoculating autoclave-sterilized soybeans with spores of a pure culture of *Aspergillus flavus* indicated that molds are primarily responsible for the characteristic initial course of spontaneous heating and respiration noted with normal soybeans.

The respiratory activity of the seed itself plays only a minor role in the course of spontaneous heating during storage. The germination of soybeans appears to be destroyed by the time the temperature rises to 45°C. (117); no germination was noted in wheat heated to 52°C. (112). The precise values for thermal destruction of germination will doubtless vary with seed species, moisture content, and duration of the heating period. Notable thermogenesis due to seed metabolism is to be expected only when the moisture value is high enough to induce germination, and even this thermogenic agency is inactivated by temperatures around 40°C.

The course of the respiratory quotient with spontaneous heating possesses certain notable characteristics (Fig. 9). The initial phase of respiration tends towards a respiratory quotient of unity. However, a sharp rise in respiratory quotient to values as high as 2.0 occurs, which is followed by an almost immediate drop. This peak in the respiratory quotient curve as the heating passes the thermal inhibition range has been shown to be associated with the gas exchange in the seed; for seeds initially autoclaved and subsequently reinoculated with the thermogenic fungi do not produce this sharp elevation in respiratory quotient. The subsequent depression in respiratory quotient to values between 0.4 and 0.5, which follows the thermal inactivation of both seeds and molds in the period of transition to rapid spontaneous chemical heating, is followed by a slow rise to values beyond unity.

The chemical changes which were followed during the heating of soybeans reveal a decrease in nonreducing sugars in the initial biological

phase, and an increase in reducing sugars coupled with a marked decrease in the fraction soluble in petroleum ether, during the chemical phase. The decrease in the petroleum-ether fraction was not accompanied by a corresponding loss in dry matter; the apparent loss in oil is probably associated with the formation of polymers which are only slightly soluble in petroleum ether.

In similar studies on the heating of wheat, Milner *et al.* (112) found that the second phase of heating, due to purely chemical oxidation, was difficult to obtain unless nearly perfect adiabatic conditions were maintained. Increases in temperature and respiration were accompanied by increases in fat acidity, decreases in nonreducing sugars, increases in reducing sugars, and a decrease in germination. The molds were all killed between 52° and 54°C., and under practical conditions the heating of wheat would not normally proceed beyond this temperature range.

In adiabatic heating trials with aerated flaxseed containing about 13.5% moisture, Schricker (139) obtained two distinct heating phases corresponding to those of Milner and Geddes (117) for soybeans; the temperature approached 100°C. in 28 days when the experiment was terminated. The data at present available indicate that the secondary heating occurs more readily with soybeans and flaxseed than with wheat; the more highly unsaturated condition of the lipids in the oil seeds may aid in promoting nonbiological oxidation. A well-authenticated case of heating in a large bulk of soybeans in commercial storage was recently brought to the attention of the authors. Heating proceeded to such an advanced stage that oil exuded from the carbonized beans and soaked through the concrete walls of the bin to form pools of oil on the ground outside. However, there was no evidence in this or other similar cases known to the authors that heating in a large undisturbed mass of grain can proceed to the point of ignition of the carbonized seeds.

Interpretation of Commercial Storage Problems in the Light of Laboratory Findings

Information gained in laboratory studies of grain storage problems has often been useful in clarifying previously obscure phenomena associated with bulk storage. But in spite of the considerable progress in this field, particularly during the past 10 years, some of these phenomena still remain unexplained.

The studies of Oxley and his co-workers (75, 125, 126, 127) have shown that a number of physical factors such as thermal conductivity,

thermal diffusivity, heat transfer by convection, the mechanics of water translocation, and gaseous diffiusion need to be considered for a clear understanding of the nature and course of respiration and heating in a grain bulk. Measurements of the thermal properties of stored grain indicate that resistance to escape of heat from the center of a grain bulk is very high and that even minor sources of heat are sufficient to cause serious rises in temperature. Knowledge of thermal properties is also useful in estimating the influence of internal and external agencies on the rate of cooling or heating of grain, and may help to clarify the relative influence of biological factors such as insects and fungi on respiration and heating. A practical application of these concepts is the determination of the effectiveness of fumigation for insect destruction from the rate of cooling of the bulk of grain after fumigation (126).

Convection of interseed gases in a bin, due to the creation of a temperature differential in the grain bulk by a localized heating zone, will doubtless influence the course of respiration and heating in areas other than those in and adjacent to the heating zone. Thus it has been noted (114) that a small heating zone in a bin of soybeans caused the lowest concentration of carbon dioxide to occur in and below the heating zone, whereas progressively higher concentrations appeared in the more remote and cooler sections of the grain bulk. It seems probable that unless a bin is hermetically sealed, continual renewal of the oxygen supply, and continual removal of carbon dioxide and heated air, will occur at a localized heating zone and cause progressive spreading of the heating area. Humidity is a major factor in this process since it is responsible for the initiation of fungal growth and thus eventually of increased respiration and heating. The data now avilable strongly suggest that in open-top concrete bins of a type found in many grain elevators, inhibition of heating due to carbon dioxide accumulation at the point of heating may rarely if ever occur.

It has been indicated (126) that the movement of carbon dioxide due to diffusion alone is extremely small in bulk grain and occurs at a rate approximately one-third of that in quiet air. Nevertheless, renewal of oxygen in a bin may occur without intervention of convection processes since normal cyclic changes in the barometric pressure can cause an appreciable interchange of air in the bin with that of the outside atmosphere (126).

It has already been indicated that the translocation of moisture vapor due to temperature differentials in the grain may possibly create zones of high moisture content and therefore cause the initiation of mold growth in regions within the grain bulk which were originally of low moisture content. This effect has been demonstrated experimentally by

Kizel, Vasil'eva, and Tsygankova (85) who immersed a cooled glass tube in a warm bulk of grain and measured the increase in water content of the grain adjacent to the tube. A more comprehensive experiment was performed by Anderson, Babbitt, and Meredith (8) with grain maintained in a sealed box 6 feet in length, the ends of which were held at different temperatures. Experiments of this type have demonstrated strikingly the ease with which moisture vapor may be translocated from warmer to cooler areas in a grain bulk. An explanation has thus been offered of how excessive respiration and heating can appear in bins of apparently dry grain. A practical example of this effect has been documented by Carter and Farrar (36) who studied soybeans of uniform moisture content (12%) stored in a watertight farm bin. In a few weeks, as a result of the decreasing external temperatures, moisture concentrations of 16 to 19% were created in the upper layer of beans with a corresponding reduction of moisture in the central warmer bulk of the material. Other practical cases of this kind have been brought to the attention of the authors, particularly in connection with the storage of very large bulks of grain for long periods under climatic conditions where marked temperature fluctuations are the rule. The final result of moisture translocation due to temperature differences in a grain bin is often the formation of a substantial surface layer of damp, moldy, rotting, and frequently germinating seeds.

In the commercial storage of wheat in bulk, heating usually begins in localized areas where conditions are the most favorable for mold growth. It has frequently been observed that after the heating has progressed for a time, the grain gradually cools off and "hot spots" develop in other parts of the grain bulk. The translocation of moisture from the hot to cool areas appears to be a very probable explanation for this phenomenon. Heating due to mold growth will, of course, not proceed beyond about 55°C., and the laboratory experiments previously described indicate that nonbiological oxidation proceeds only with great difficulty in wheat, even under optimum conditions of aeration and insulation (110). The thermal inactivation of the fungi would therefore result in the cessation of heating in such an area and in the slow cooling of the grain due to the dissipation of the heat.

Outlook for Future Research

The concept that fungi play an important part in the respiration and heating of damp grain has received wide acceptance only within the last several years, and additional researches are necessary before the role of microflora in seed deterioration is conclusively and convincingly established.

It would be desirable to measure respiration, heating, and deteriorative changes of viable seed absolutely free of all bacteria, yeasts, and molds, and to measure similar changes in seed originally free of microorganisms but inoculated with known microflora that occur on the seed, both singly and in combination. Such tests require seed absolutely free of microorganisms, and it is difficult to obtain, at least in quantities sufficient for laboratory tests. The expenditure of considerable time, talent, and expense would be justified in conducting experiments of this nature if a method for the production of sufficient quantities of sterile, viable seed could be developed.

It would also be desirable to determine when, how, and under what circumstances various microorganisms invade the seed, how they affect the seed, and the relation of mycelium established within the seed to subsequent deterioration in storage. Oxley (125) has noted the occurrence of fungus mycelium under the pericarp, but there has been no direct evidence that the mycelium is alive, or that the fungi are significant in storage deterioration. Christensen (39) has recently obtained evidence that, in high-quality wheat seed, most of the mycelium present under the pericarp was that of *Alternaria,* a fungus of no significance in storage deterioration. More extensive and more critical work than that published to date is needed to determine the effect of subepidermal mycelium upon seed quality and upon deteriorative changes in storage.

There have been very few studies on the role of bacteria in relation to deterioration of stored grain because they do not grow readily until the moisture content of the grain exceeds that in equilibrium with a relative humidity of 90 to 95%. Bacteria are known to be present in relatively large numbers on most agricultural seeds and their relation to storage deterioration at high moisture contents should be determined.

A few workers have been interested in a search for effective fungistatic and fungicidal agents which might be applied to damp grain to prevent heating. The problem is a difficult one since a number of compounds used for the treatment of grain for seed purposes have been found to be quite ineffective against the microorganisms responsible for the deterioration of stored grain. Any chemicals used for this purpose must be economical and without any effect upon the utility of the grain for food or fermentation purposes. Evidence has also been presented to show that high-moisture grain in which mold growth is prevented will develop undesirable flavors and odors upon storage; and, with wheat, deleterious changes in baking properties are not entirely prevented. Despite these difficulties, mold inhibitors may be found which will prove valuable for the short-time storage of high-moisture grain. Such inhibitors would prevent spoilage until the grain could be fed or dried to safe

moisture levels.

Another potential means for the preservation of damp grain which has not yet been adequately investigated is exposure to the sterilizing effect of high intensity beta or gamma radiation, a process which would not cause heating of the grain. The effectiveness of such electromagnetic radiations for sterilizing a number of other foods has been demonstrated (132a), and it is reasonable to expect that similar inhibition of spoilage due to microorganisms in stored grain may be possible. The use of radioactive isotopes as gamma ray sources would probably be more feasible for this purpose than mechanical or electrical means for generating beta or other radiations, although many technical difficulties need to be overcome before such a process could be made practical and economically feasible. Many radioactive isotope materials obtained as by-products in nuclear reactors, and which conceivably could be utilized for sterilization purposes, are now wasted (152a).

"Sick" wheat continues to be a vexing problem to the grain trade. The studies which have been reported indicate that "sick" wheat may be the end result of any one of several different processes, or combinations of them. If seed is stored moist, or if it becomes moist in storage, fungi (and sometimes bacteria) invade and kill the embryo, and soon after death it turns brown. The embryos of seed stored under atmospheres of carbon dioxide or nitrogen at moisture contents of 18–20% die and turn brown in the apparent absence of active growth of microorganisms. The germs of seed stored dry for years gradually die and turn brown. The nature of this pigmentation remains to be determined. It is possible that oxidase enzymes may be involved. The occurrence of elevated fat acidity values in "sick" wheat suggests that lipase activity bears some relationship to the discoloration. However, no positive evidence is available on this point. Controlled studies of various factors that kill and discolor the germ are needed. In such researches, it would be preferable to employ seed which is known to be absolutely free of microflora, so that one might distinguish deteriorative changes of the seed itself from those induced by fungi, bacteria, and yeasts.

There is strong circumstantial evidence that a browning phenomenon, purely chemical in nature, which involves interaction of reducing materials such as sugars with proteins, may be responsible for the pigmentation. This hypothesis derives from the fact that the discoloration in "sick" wheat may appear at moisture values well below those at which biological activity can be postulated and particularly at elevated temperatures (110). It is significant, also, that wheat embryos contain high concentrations of both free sugars and protein. At present, however, the available evidence indicates that fungi are the major cause of the "sick"

wheat condition.

The extent to which information obtained in the laboratory, concerning the cause of spontaneous heating in grain, may be applied to conditions found in large commercial bins undergoing heating is yet to be determined. While it appears most probable that the two-phase course of spontaneous heating in stored grain, which has been detected in laboratory studies (the first caused by fungi and ending at about 55°C. and the second producing even higher temperatures due to nonbiological oxidation), occurs in bins as well, there remains to be determined the influence of grain bulk and other phenomena associated with bulk on the course and final outcome of the nonbiological phase of heating.

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CHAPTER V

Insects

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Insects that attack our stores of cereal foods constitute one of the most serious threats to our present civilization. It is said that the civilization of the world owes its development in no small part to the discovery by ancient man of the food value of grain and its products. Large quantities of nutritious grain foods could be grown, stored, and prepared with ease, thus not only insuring against famine, but permitting man to devote his energy to pursuits other than the constant search for food. By allowing insects to take a yearly toll of our stores we deprive millions of people of the possibility of economic development and the social and political stability that characterizes the well fed.

It is estimated that insects destroy at least 5% of the world production of cereals, wheat, corn, rice, barley, oats, and rye. As the result of a survey on world losses to cereals from pests, conducted in 1947 by the United Nations Food and Agriculture Organization, it was estimated that for the 29 countries surveyed, the total annual loss was 25,750,000 metric tons, of which 50% could be attributed to insects. This is a very conservative figure for world losses since all countries were not included in the survey and some of the countries failed to include losses to grain in farm storage.

These huge losses to our cereal grains from insect attack are unnecessary. Information is available that if publicized and utilized could prevent a large proportion of these losses. The following pages may help to serve this end by describing the insects that prey upon our stored cereal foods, the conditions under which they thrive and multiply, and the methods that have been found most effective and economical in preventing their depredations.

The Important Species

The insects most destructive to our stored cereal grains originated in those portions of the world where wheat, barley, and rice were the principal grain foods. They have been carried by commerce to all parts

of the world. In the days of the sailing vessels, grain and other dry food materials were invariably swarming with insects at the end of long voyages, and there is little doubt that supplies of grain brought to North America by the colonists for seed and food were heavily infested with insects. History records that many of the early colonists would have quickly starved had it not been for the supplies of corn they obtained from the American Indians.

Several hundred different species of insects are found associated with stored grains and their products (7, 15, 19, 20, 29, 34, 38). Fortunately, only a small portion of them cause serious damage to products that are in good condition. Many of them are attracted only to dried vegetable materials that are beginning to spoil; they feed on the molds and fungi growing on such products. Others are predators or parasites that attack the true grain pests, and are present only in the role of benefactors. About 50 species are seriously injurious to stored grains and grain products.

Conditions in all parts of the world are not equally favorable for the development of all of these insects, so that species that are of major importance in some sections are barely able to exist in others. In the discussion that follows, particular reference will be made to the species of grain-infesting insects that are of greatest importance in North America. However, mention will be made of those species that, while uncommon on the American continent, are of economic importance in other parts of the world. A list of the species discussed is given in Table I.

Many of these insects can be readily identified by reference to illustrations appearing in publications by Back and Cotton (7), Cotton (15), Freeman and Turtle (29), and Munro (38). Simple keys that are useful for identifying the common insect pests of stored grain and milled grain products have been published by Hinton and Corbet (34).

True Grain Weevils. The most destructive pests of stored grains are the ones that can break through the tough seed coat to reach the softer endosperm. They are generally classed as weevils. Undoubtedly the two most important members of this group of grain destroyers are the rice weevil (Fig. 1, E), *Sitophilus oryza* (L.), and the granary weevil (Fig. 1, C), *S. granarius* (L.). They are truly cosmopolitan in distribution. Both of these insects are small, reddish-brown to dark-brown beetles about ⅛ in. long. Like other members of the weevil family, their mouth parts are prolonged into a more or less elongated snout. They resemble each other so closely that it is difficult for the layman to tell them apart. However, the rice weevil is marked on the back with four light-reddish or yellowish spots and is further differentiated from the

TABLE I

ALPHABETICAL LIST OF THE INSECT AND MITE PESTS OF STORED GRAIN REFERRED TO IN THIS CHAPTER

Scientific Name	Common Name	Classification
Acarus siro L.	Flour or grain mite	Major pest
Ahasverus advena Waltl.	Foreign grain beetle	Scavenger
Alphitobius piceus Oliv.	Black fungus beetle	Scavenger
Aplastomorpha calandrae How.	None	Parasite
Araecerus fasciculatus Deg.	Coffee bean weevil	Minor pest
Attagenus piceus Oliv.	Black carpet beetle	Minor pest
Carpophilus dimidiatus F.	Corn sap beetle	Scavenger
Caulophilus latinasus Say	Broad-nosed grain weevil	Minor pest
Corcyra cephalonica Staint.	Rice moth	Minor pest
Cynaeus angustus Lec.	Larger black flour beetle	Minor pest
Ephestia cautella Wlkr.	The almond moth	Major pest
Ephestia elutella Hbn.	Tobacco or cacao moth	Major pest
Ephestia kühniella Zell.	Mediterranean flour moth	Major pest
Laemophloeus spp.	Flat grain beetles	Major pest
Lasioderma serricorne F.	Cigarette beetle	Minor pest
Latheticus oryzae Waterh.	Long-headed flour beetle	Minor pest
Microbracon hebetor Say	None	Parasite
Omphrale fenestralis L.	Window pane fly	Predator
Oryzaephilus surinamensis L.	Saw-toothed grain beetle	Major pest
Plodia interpunctella Hbn.	Indian-meal moth	Major pest
Ptinus hirtellus Sturm.	Brown spider beetle	Minor pest
Ptinus villiger Reit.	Hairy spider beetle	Minor pest
Rhyzopertha dominica F.	Lesser grain borer	Major pest
Sitophilus granarius L.	Granary weevil	Major pest
Sitophilus oryza L.	Rice weevil	Major pest
Sitotroga cerealella Oliv.	Angoumois grain moth	Major pest
Stegobium paniceum L.	Drug-store beetle	Minor pest
Tenebrio spp.	Meal worms	Minor pest
Tenebroides mauritanicus L.	Cadelle	Major pest
Tinea granella L.	European grain moth	Minor pest
Tribolium castaneum Hbst.	Red flour beetle	Major pest
Tribolium confusum Duv.	Confused flour beetle	Major pest
Tribolium madens Charp.	Black flour beetle	Minor pest
Trogoderma granarium Everts	Khapra beetle	Major pest
Trogoderma versicolor Creutz.	Larger cabinet beetle	Minor pest
Typhaea stercorea L.	Hairy fungus beetle	Scavenger

granary weevil by the possession of functional wings. This latter characteristic makes the rice weevil of greater importance than the granary weevil, because in warm climates it can fly to the fields and attack the grain before it is harvested. Furthermore, it spreads from infested grain to uninfested grain by flight.

The weevils use their elongated snouts to bore through the tough seed coat of the grain to reach the endosperm. In addition, with their snouts they excavate a long slender cavity in which to place their eggs. The snout can excavate a hole deep enough to contain the egg, with enough space left for a gelatinous cap that seals the egg in place and protects it from damage. After the cap or plug is in place it is impossible to see where the egg has been laid, unless the kernel of grain is exam-

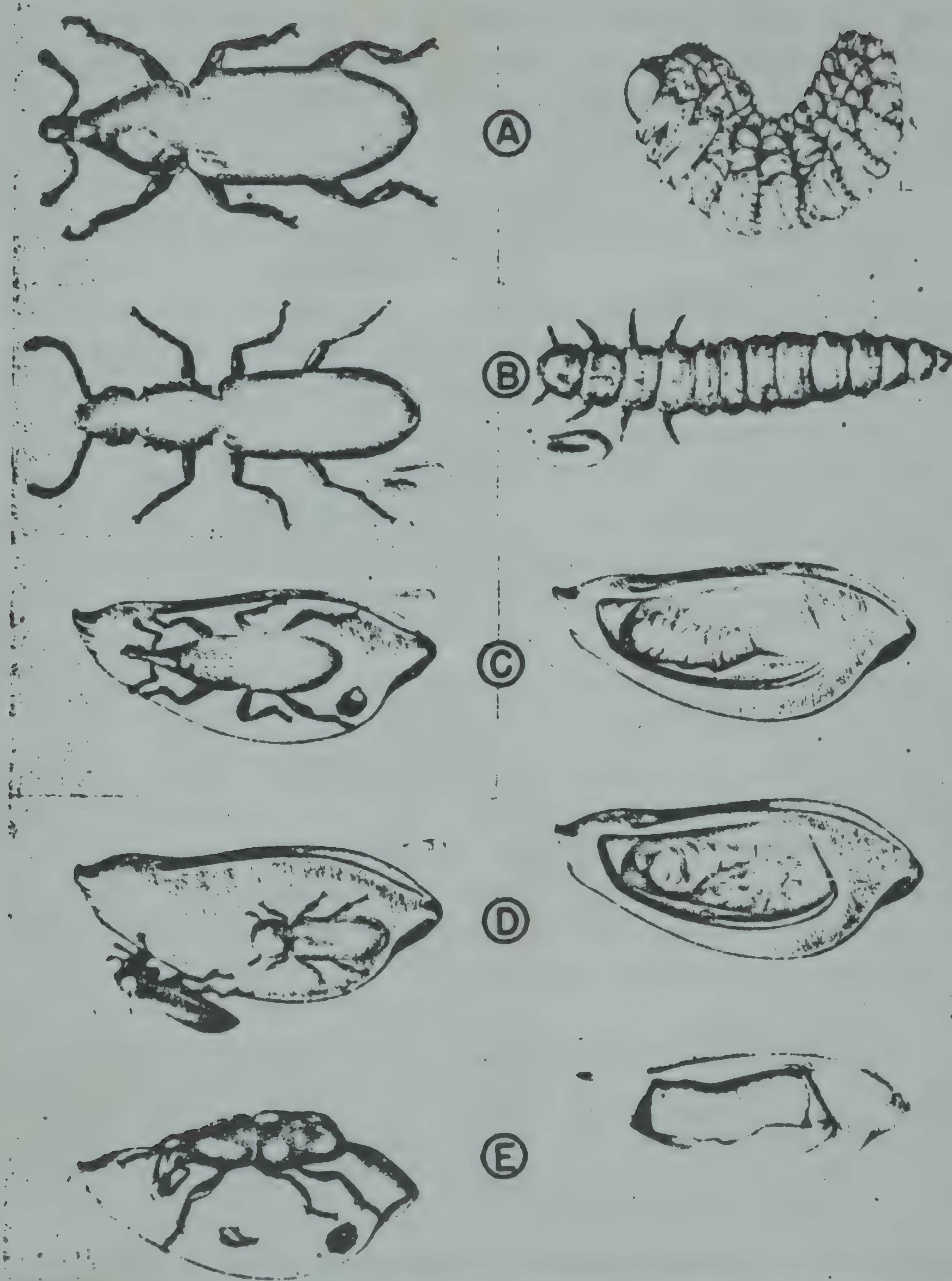

Fig. 1. Adults and larvae of: A, Broad-nosed grain weevil; B, Saw-toothed grain beetle; C, Granary weevil; D, Lesser grain borer; and E, Rice weevil.

ined under a magnifying glass or treated with a stain that will color the egg plug.

The egg hatches in a few days into a small, fleshy, white grub which finds itself surrounded by nutritious food. The grub feeds on the endosperm of the grain until it completes its growth and then changes to a pupa or resting stage. A few days later it transforms to an adult weevil, which cuts its way out of the grain. By passing the developmental period within the grain the defenseless immature stages of the

weevil are protected from predaceous enemies and sudden destructive changes in temperature.

Under favorable conditions of moisture and temperature the weevils may complete their development from newly laid egg to adult in four weeks. With each female weevil capable of laying several hundred eggs, an enormous increase in numbers is possible and frequently occurs in comparatively short periods.

The size of the weevil depends somewhat on the size of the kernel of grain. In small grains such as millet or grain sorghum, the weevil will be small, but in corn it will attain its maximum size. The great variation in the size of the rice weevil, resulting from the quantity of food available in the seed, has caused many people to consider the small and large forms to be different varieties or species. This is sometimes true. In 1944 Birch (10) reported the existence in Australia of two strains of the rice weevil that differed in size and were intersterile. He referred to them as the "large strain" and the "small strain." Richards (42) also reported the existence of two strains of this weevil in England.

These weevils are rarely found breeding in anything except seeds. However, they can and do breed in solid-milled cereal products, such as macaroni, and have occasionally been found breeding in tightly packed flour.

The lesser grain borer (Fig. 1, D), *Rhyzopertha dominica* (F.), has similar habits but, in its grub stage, can also feed outside the kernel on the flour or grain dust made by the feeding adults. Although one of the smaller beetles injurious to stored grain, this borer is capable of doing great damage. The grubs and beetles together completely hollow out the kernels of grain so that only the outside shell is left. Moreover, this beetle frequently breeds in flour that has been held in storage for some time. When found in grain samples it is classed by grain inspectors as a weevil. It is particularly destructive to stored grain in India, Australia, the southern portion of the United States, and in other areas with warm climates, but it is not of great importance in England and in European countries with similar climates.

Other beetles that spend their immature life concealed within the kernel of grain are the broad-nosed grain weevil (Fig. 1, A), *Caulophilus latinasus* (Say), and the coffee bean weevil (Fig. 2, D), *Araecerus fasciculatus* (Deg.). Both of these are minor pests.

Moths. One other insect that spends its immature life within the kernel of grain is the Angoumois grain moth (Fig. 2, C), *Sitotroga cerealella* (Oliv.). It is cosmopolitan in distribution and, as a pest of stored grain, is second in importance only to the weevils and the lesser

Fig. 2. A, Flat grain beetle, adult; B, Rice moth, adult; C, Angoumois grain moth, adult; D, Coffee bean weevil, adult; E, Confused flour beetle, adults, larvae, and pupae; F, Grain mites.

grain borer. The moth lays its eggs on grain in storage or when it is still in the field. The young grubs or caterpillars, which hatch from the eggs, burrow into the kernels and complete their development hidden from view. Before transforming to the pupal stage the caterpillar makes an escape tunnel to the outside of the seed, leaving only a thin layer of the seed coat intact for the moth to burst through as it leaves the grain. The soft-bodied moths are unable to force their way below the surface of binned grain so that the greatest damage occurs to wheat

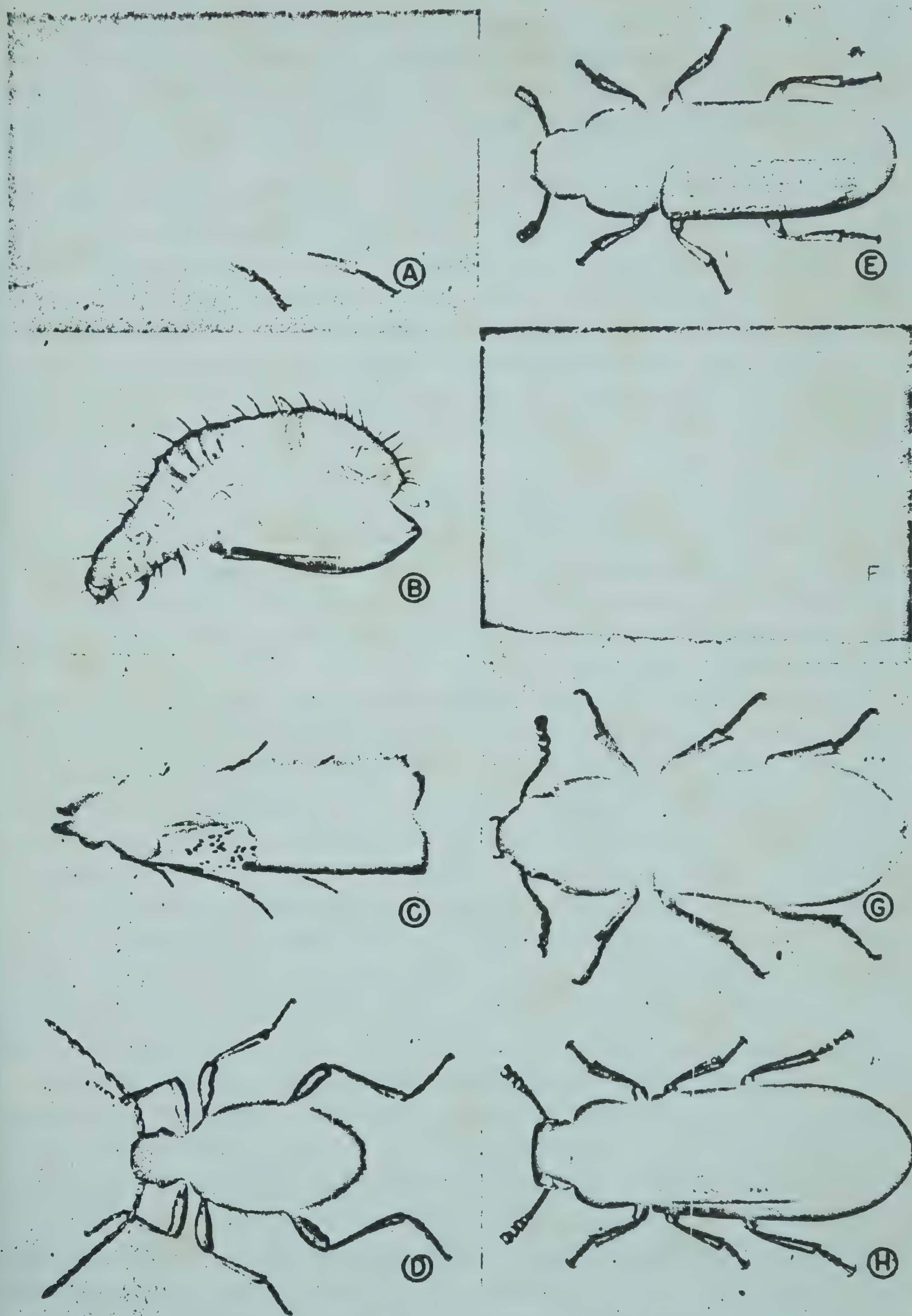

Fig. 3. A, Dark meal worm, adult; B, Indian-meal moth, larva; C, Indian-meal moth, adult; D, Hairy spider beetle, adult; E, Red flour beetle, adult; F, Cadelle, larvae; G, Cadelle, adult; and H, Black flour beetle, adult.

in the shock or mow before threshing. In areas where wheat is harvested with a combine harvester no trouble is experienced with the moth. In the southern portion of the commercial corn area and in the southern states, field infestation of corn by this moth is occasionally quite severe.

A number of moths that are general feeders on stored foodstuffs occasionally attack stored grain. The most important one in North America is the Indian-meal moth (Fig. 3, B and C), *Plodia interpunctella* (Hbn.). It is also reported as troublesome to stored grain in India but does not appear to be of much importance as a pest of stored grain in England and Europe. A rather handsome moth, it can be easily recognized by the markings of its forewings. These are reddish brown with a coppery luster on the outer two-thirds, but whitish gray on the inner or body end, so that when the moth is at rest it appears to be marked with a prominent brown band. It attacks grain of all kinds in bags, cribs, or bins, laying its eggs at random among the kernels. The larvae occasionally appear in tremendous numbers webbing over the surface of grain with silken threads that form a thick carpet. As with most species of moths that attack stored grain, the larvae prefer the germ to the endosperm.

In England and Europe the tobacco moth, *Ephestia elutella* (Hbn.), is at times an important pest of bulk stored wheat. It does not appear to be troublesome in this respect in the United States. However, the closely related almond moth, *E. cautella*, is a serious pest in seed stores in the southern portion of the United States where it attacks seed corn, small grains, beans, and cowpeas. It is also troublesome in bulk storages of rough rice and grain sorghum and has occasionally been found infesting bulk wheat. The European grain moth, *Tinea granella* L., is also considered an important pest of stored grain in England and Europe; it is of no importance in the United States. The rice moth (Fig. 2, B), *Corcyra cephalonica* (Staint.), is considered important as a pest of stored grain in India; it is a common pest of rough rice in the United States.

Bran and Flour Beetles. A large group of beetles that are cosmopolitan in distribution and that feed on broken grain, on the germ portion of grain kernels, on grain dust, or on flour and similar products, are commonly called "bran bugs" and are sometimes referred to as "bran beetles" or "flour beetles." Their eggs are usually laid indiscriminately among the kernels, and the larvae are for the most part free-living. An exception is the larva of the flat grain beetle that prefers to burrow in the germ of the grain. These beetles are usually reddish brown in color and vary in length from 1/16 to 1/7 in. The presence of any of these bran beetles in large numbers in stored grain induces

heating in the interior of the grain mass. This is followed by spoilage of the cool surface grain owing to the condensation in it of water vapor rising from the warmer infested grain below. The most abundant species are the flat grain beetles (Fig. 2, A), *Laemophloeus* spp., and the saw-toothed grain beetle (Fig. 1, B), *Oryzaephilus surinamensis* (L.). However, the most important species are the red flour beetle (Fig. 3, E), *Tribolium castaneum* (Hbst.), and the confused flour beetle (Fig. 2, E), *T. confusum* Duv., since they are carried with grain supplies to flour mills where they are easily the worst insect enemies of the miller. Of the two species, *T. castaneum* is the predominant form infesting stored grain. This is due to the fact that this species flies, whereas *T. confusum* does not. The black flour beetle (Fig. 3, H), *T. madens* (Charp.), is another member of this genus that is occasionally found in stored grain and flour mills.

One other beetle worthy of special mention is a black beetle about ⅓ in. long, known as the cadelle (Fig. 3, F and G), *Tenebroides mauritanicus* (L.). The large fleshy larvae of this insect burrow into the woodwork of grain bins in the autumn to hibernate and remain there for long periods, so that they are difficult to eliminate when farmers clean out their bins preparatory to filling them with new grain. Seemingly clean and empty bins frequently harbor hundreds of these insects which come out of their hiding places to attack new grain.

The Khapra beetle *(Trogoderma granarium* Everts) is an important pest of stored grain in India. This dermestid beetle has been widely distributed over the world by commerce and has become established as a minor pest in English malt houses. It has been reported as occurring in Egypt, Australia, and various parts of Europe and Asia. Only recently it has become established in California. Related species, *T. versicolor* (Creutz.) and *Attagenus piceus* (Oliv.), have similar habits, are cosmopolitan in distribution, but are of no great importance as destroyers of stored grain.

A rather curious group of beetles known as spider beetles from their superficial resemblance to spiders are omnivorous feeders and are occasionally troublesome as pests of stored grain and milled cereal products in cool climates. They are not troublesome in the United States, but the brown spider beetle, *Ptinus hirtellus* Sturm., is destructive in England and the hairy spider beetle (Fig. 3, D), *P. villiger* (Reit.), in Canada.

Mites. Grayish-white, smooth, wingless, soft-bodied creatures almost microscopic in size are occasionally found in stored grain. They are known as mites (Fig. 2, F) and are not true insects since the adults have eight legs instead of the six which are characteristic of true insects.

Although several different species of mites may be found in stored grain they are not all destructive. Some of them are predaceous on the mites that damage grain. The most destructive species of mite infesting grain is *Acarus siro* L. (46, 47). It is particularly fond of the germ, although it will feed on other parts of the grain or on the molds growing on grain.

Scavengers. Insects that feed on decaying grain or on the molds developing on it constitute a large portion of the species reported as grain-infesting insects. They cannot be considered as beneficial in the sense that scavengers of carrion are considered useful in disposing of decaying material; on the other hand, they do not cause great damage to stored grain unless they are present in very large numbers. In such cases they may cause heating and thus aggravate the conditions that cause spoilage. Meal worms (Fig. 3, A), *Tenebrio* spp., the hairy fungus beetle, *Typhaea stercorea* (L.), the foreign grain beetle, *Ahasverus advena* (Waltl.), the corn sap beetle, *Carpophilus dimidiatus* (F.), and the black fungus beetle, *Alphitobius piceus* (Oliv.), are typical examples.

Associated Insects. Numerous parasites and predators of grain-infesting insects may at times be seen crawling over the surface of stored grain. Although they are beneficial, many people mistake them for the enemies of grain.

One of these is a small wasplike creature known as *Aplastomorpha calandrae* (How.). It is the most important parasite of the rice and granary weevils. The female wasp, crawling over infested kernels, is able to detect the presence of a weevil grub hidden from sight within the grain. She paralyzes the weevil grub with a few quick thrusts of her ovipositor, then lays a single egg on or near the grub. The egg hatches and the parasite grub feeds on the weevil grub, thus destroying it. Another member of the group of parasitic wasps frequently seen in great numbers in stored grain is *Microbracon hebetor* (Say). This wasp parasitizes the larvae or caterpillars of a number of the common grain-infesting moths such as the Indian-meal moth and the Mediterranean flour moth (*Ephestia kühniella* Zell.).

A small threadlike white worm often seen in accumulations of grain or grain dust is the larva of the window pane fly, *Omphrale fenestralis* (L.). It is a predator by habit and lives at the expense of grain-infesting insects that it encounters. Anthocorids, members of the true bug family, are also predaceous on grain-infesting insects and are often found in bins of grain. They do not damage the grain in any way. A minute pseudo scorpion, *Chelifer cancroides* (L.), preys upon mites and small insects in stored grain and, although not of economic importance, attracts attention by its odd appearance.

Species Most Destructive to Cereal Products. With the milling of

grain the softer endosperm is exposed to the attack of insects. Many species that breed with difficulty in sound, unbroken grain multiply rapidly in milled cereal products. This is particularly true of the flour beetles. According to the calculations of Gray (31) the progeny of a single pair of the confused flour beetle breeding in flour, could, if undisturbed, reach the staggering total of over one million in 150 days. The much slower rate of reproduction of this insect in grain is shown in Figure 4.

The confused flour beetle and the red flour beetle are the most destructive insect pests of milled cereals, and in North America constitute more than 80% of the insect population of flour mills. In the central states the two species are about equally abundant in flour mills. In the South the red flour beetle is most common, whereas in the North and in Canada the confused flour beetle is the predominant species in mills.

Next to the flour beetles, the Mediterranean flour moth is the most destructive pest in flour mills in North America. In England and European countries it is considered to be more troublesome in mills than the flour beetles. It is a serious pest both in the mill and the warehouse, and is one of the few insects that thrive on a diet of pure endosperm.

The Indian-meal moth prefers the germ and bran and according to Fraenkel and Blewett (26) fails to grow on a diet of patent flour alone. Nevertheless, it is one of the worst and most widely distributed of the insect pests of cereal products.

Although most of the insect pests of stored grain also feed on milled cereals, there are a few that are more destructive to these products than the rest. The cadelle is one of these. Owing to its habit of burrowing into woodwork it is often found in mills that have wooden elevator boots and also in the woodwork of railway cars and storage warehouses. Consequently, milled cereals are frequently invaded by this insect during storage or transit. In the days when it was customary to recondition infested flour for blending purposes it was not uncommon to see cadelle larvae screened out by the thousands.

The saw-toothed grain beetle and the flat grain beetle are exceedingly common in warehoused cereal products. As a result of their small size and flat shape they can easily penetrate packages of all types. Although they do not actually destroy much food their presence renders it unfit for human consumption.

In countries with cool climates, Ptinid beetles are quite troublesome as pests of cereal products in storage. In England the brown spider beetle is particularly destructive, whereas in Canada the hairy spider beetle is a serious pest of flour warehouses. According to Freeman and Turtle (29) the brown spider beetle is now the most widespread and

common stored-product pest in England. The fully grown larvae may bite holes in the surface of sacks of flour. When infestations are severe, the whole inside of the flour sacks may be covered with cocoons and the bag fabric so weakened as to tear easily.

Mites are particularly troublesome in milled cereal products in countries with a cool, moist climate. According to Freeman and Turtle (29) the flour mite, *Acarus siro* (L.), is the principal pest of stored wheat, flour, and wheat offals in England except in warm, dry stores.

Species Most Abundant in the United States. Although the insects that attack stored grain are rather general feeders and may be found feeding on many kinds of grain, some of them show a distinct preference for certain grains. In the commercial corn area, including Illinois, Iowa, Nebraska, Minnesota, and South Dakota, records over a 3-year period showed that the following six species were more commonly found in stored shelled corn than any others and constituted more than 98% of the insect population: saw-toothed grain beetle, flat grain beetle, red flour beetle, foreign grain beetle, larger black flour beetle, *Cynaeus angustus* (Lec.), and hairy fungus beetle. Of these species, the first three comprised the greater portion of the insect population. In the South where field infestation is universal, the rice weevil is by far the most abundant species and constitutes the largest proportion of the insect population of stored corn.

In the Great Plains hard winter wheat region, seven species constitute over 90% of the insect population of wheat in farm storage. They are the flat grain beetle, the saw-toothed grain beetle, the lesser grain borer, the red flour beetle, the long-headed flour beetle *(Latheticus oryzae* Waterh.), the cadelle, and the rice weevil. The abundance of these insects varies with climatic conditions. In the northern portions of the region the hardier species, the flat grain beetle and the saw-toothed grain beetle, are predominant; whereas in the southern portion of the area the lesser grain borer and the rice weevil become increasingly abundant. Along the Eastern Seaboard the Angoumois grain moth is occasionally one of the common pests of stored wheat, although ordinarily the flat grain beetle and the rice weevil are the predominant species in that region. The insects found in greatest abundance in rough rice in storage are the Angoumois grain moth, rice weevil, flat grain beetle, lesser grain borer, and red flour beetle.

Ecology

The insect pests of stored grain have certain temperature, moisture, and food requirements which directly affect their abundance and hence their ability to cause damage.

Temperature. As a group, these insects are mostly of subtropical origin and do not hibernate. They have not developed resistance to low temperatures so that in the northern portions of North America they are rarely abundant enough to cause serious damage to grain in storage. A thorough knowledge of the limiting effect of low temperatures will be found invaluable in formulating management programs for the safe storage of grain. Records of the relative susceptibility of various stored grain insects to low temperatures are given in Table II.

TABLE II

RESISTANCE TO LOW TEMPERATURES OF VARIOUS INSECTS THAT ATTACK STORED GRAIN AND GRAIN PRODUCTS (Cotton, 15)

Insect	Days Exposure Required to Kill All Stages at						
	0°-5°F.	5°-10°F.	10°-15°F.	15°-20°F.	20°-25°F.	25°-30°F.	30°-35°F.
Rice weevil	1	1	1	3	6	8	16
Granary weevil	1	3		14	33	46	73
Saw-toothed grain beetle	1	1	3	3	7	23	26
Confused flour beetle	1	1	1	1	5	12	17
Red flour beetle	1	1	1	1	5	8	17
Indian-meal moth	1	3	5	8	28	90	..
Mediterranean flour moth	1	3	4	7	24	116	..

Temperatures that are not quickly lethal indirectly cause the death of many insect pests of stored grain by rendering them inactive and preventing them from feeding. Since they do not hibernate, their life processes are not sufficiently retarded by low temperatures to allow the food reserves of their bodies to sustain them through an extended period of dormancy; as a result, they die from starvation. A few insects such as the cadelle do hibernate and are capable of surviving exposure to low temperatures for long periods.

According to Robinson (45) the rice weevil is dormant at temperatures of 45°F. or below and the granary weevil at 35°F. or below. Anderson (4) noted that neither species mated when the temperature falls below 53.6° to 55.4°F. Although Richards (43) has placed the lower limit of oviposition at 49.1°F., most writers agree that few eggs are laid at temperatures below 60°F. Hatching and development of larvae at temperatures between 55° and 60°F. are extremely slow. Bran beetles, of which the red flour beetle and saw-toothed grain beetle are typical, do not lay eggs at 60°F.; hence breeding ceases at that temperature. Tyroglyphid mites are able to breed in stored wheat at temperatures between 40° and 50°F. if moisture conditions are favorable.

Subject to certain upper limits, the rate of development and reproduction of all grain-infesting insects increases with rising temperatures. A grain temperature of 70°F. is considered to be the danger line. At that or higher temperatures severe damage to stored grain from insects

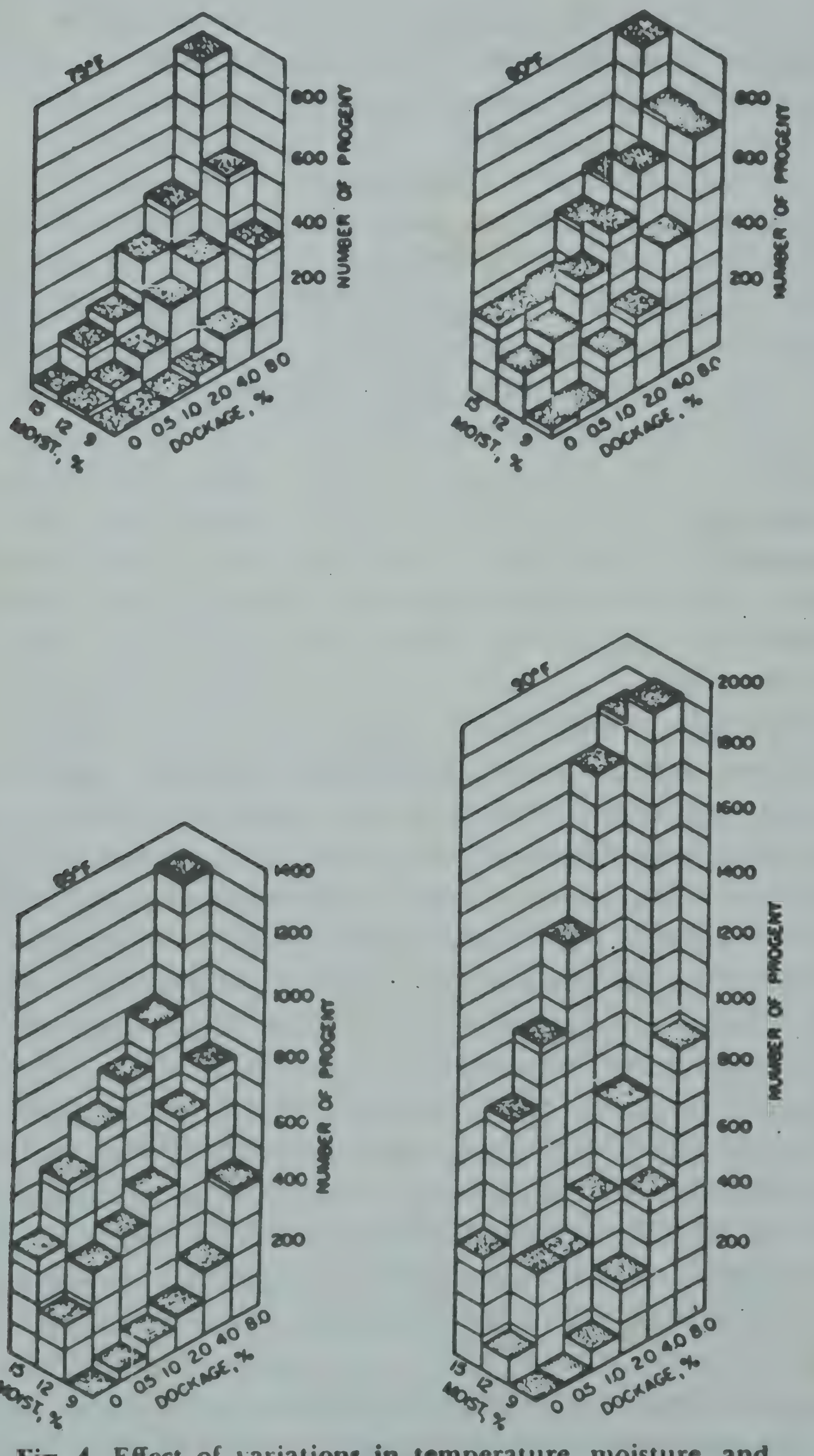

Fig. 4. Effect of variations in temperature, moisture, and dockage present in wheat on the reproduction of 25 confused flour beetles over a 19-week period. (After Cotton and Frankenfeld, 16.)

may be expected, whereas below this temperature level no serious damage is likely to occur. The effect of temperature on the reproduction of the confused flour beetle in wheat is shown graphically in Figure 4 (Cotton and Frankenfeld, 16). This response to temperature is typical of this group of insects. With few exceptions, temperatures above 95°F. are unfavorable for reproduction, oviposition ceases, and adults are short-lived. The lesser grain borer is one exception. Reproduction of this species at temperatures of 100°F. have been recorded by Gay and Ratcliffe (30).

Temperatures above 100°F. soon cause the death of most insects, although an extreme case of adaption to high temperatures has been recorded by Von Wahl (50) who observed the grain mite, *Acarus siro* (L.), living in fermenting tobacco at a temperature of 131°F. For sterilizing milled cereals by heat, a temperature of 140°F. for 10 minutes is considered effective against all cereal-infesting insects.

The effect of temperature in limiting the regional abundance of various species is quite pronounced. After a series of mild winters the Angoumois grain moth is troublesome in the soft winter wheat region of the Atlantic Seaboard in states as far north as New York and in the commercial corn area to a line passing through the southern half of Illinois and Indiana. On the other hand, it is never troublesome after a severe winter. The lesser grain borer is similarly restricted by climatic conditions to the southern states. It is not troublesome in grain in farm storage north of central Kansas. The granary weevil is much more abun-

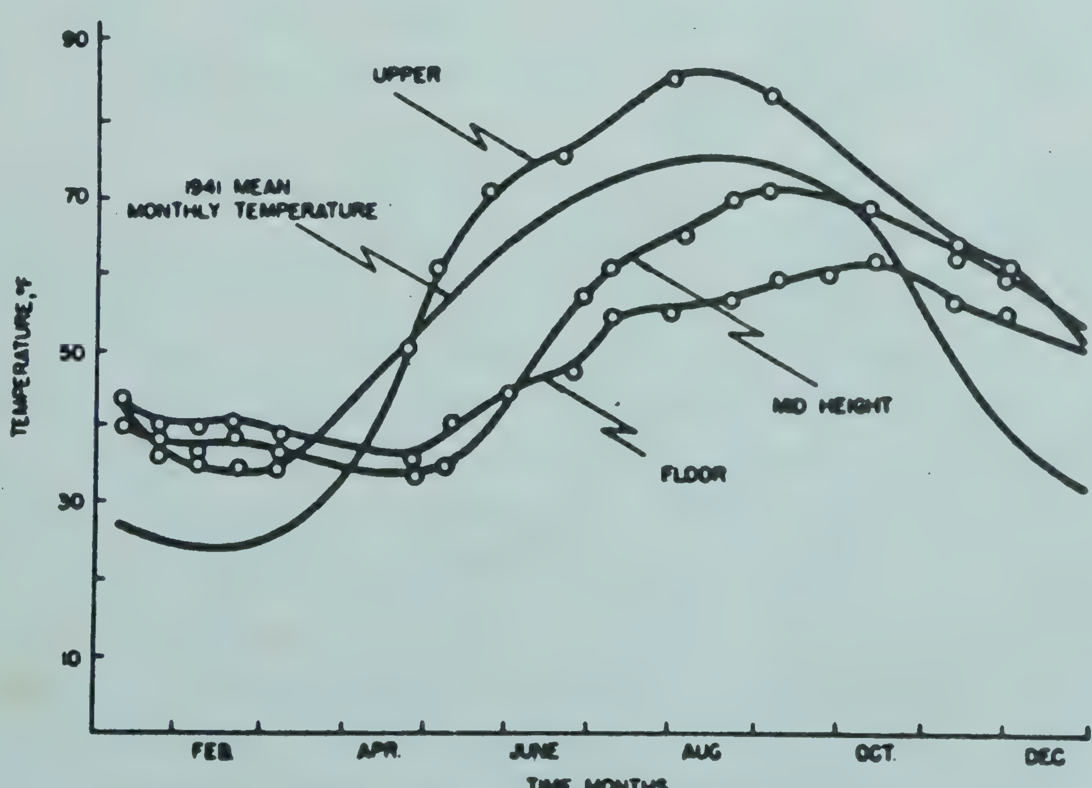

Fig. 5. Temperatures observed at various heights in the center of a bin of shelled corn at Ogden, Iowa, from January 10, 1941, to January 27, 1942. (After Barre and Cotton, 9.)

dant in the northern states than in the South, whereas with the rice weevil the reverse is true. Mites are seldom troublesome in stored grain in the United States but are common in the cooler climates of Canada, England, Russia, etc. In corn stored in the commercial corn area, and wheat stored in regions with a similar climate, the flat grain beetle and the saw-toothed grain beetle survive winter temperatures better than other grain-infesting species. Undoubtedly this accounts for their greater abundance in grain stored in this region. Grain temperatures typical for the commercial corn area throughout the year are indicated in Figure 5 (Barre and Cotton, 9).

Moisture. The insect pests of stored grain depend on their food supply for the moisture needed to carry on their life processes. For this reason grain moisture is an important factor in their life economy. Up to a certain point (Table IV) increasing moisture favors a rapid increase in the numbers of insects breeding in grain. If, on the other hand, the moisture content of the grain is low, the water required for carrying on the vital life processes can be obtained only by breaking down the food supply or the food reserves of the body. The moisture requirements naturally differ with different species of insects, as does the ability of these insects to produce the water they need. The rice and granary weevils are unable to breed in grain with a moisture content below 9%, and the adults soon die in dry grain. The effect of grain moisture on the survival of adult rice weevils is indicated in Figure 6, and the effect of grain moisture on the reproduction of the rice weevil

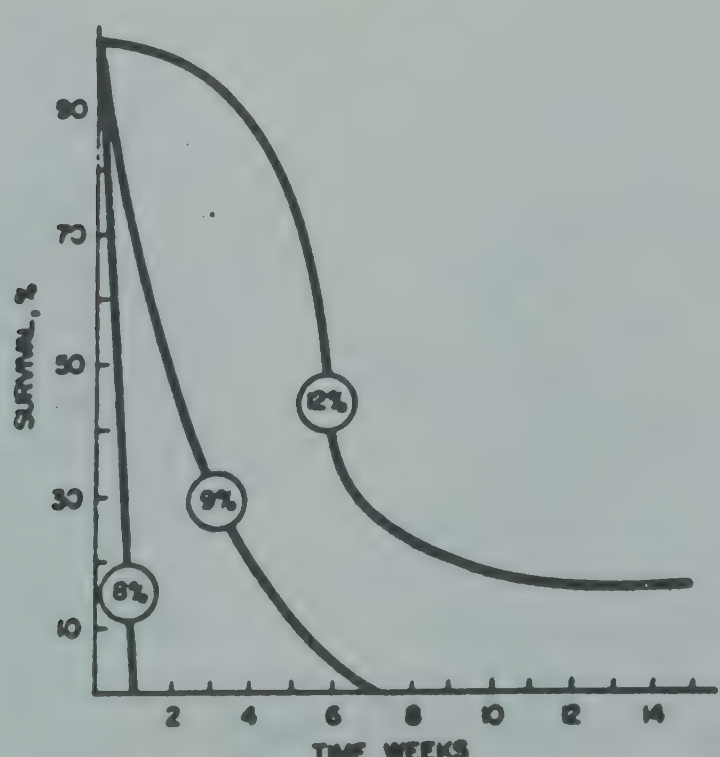

Fig. 6. Survival of rice weevil adults at 85°F. in wheat samples of different moisture content. (Unpublished notes, Cotton and Frankenfeld.)

at temperatures of 70° to 90°F. is indicated by the data of Table III. It is interesting to note that the temperature has a direct influence on the ability of the weevil to breed in grain. As the temperature rises, the ability of the weevil to reproduce in dry grain increases. In high moisture grain, the rate of reproduction appears to fall off at temperatures above 80°F.

TABLE III

REPRODUCTION OF THE RICE WEEVIL AS AFFECTED BY THE TEMPERATURE AND MOISTURE CONTENT OF GRAIN (Unpublished notes, R. T. Cotton and J. C. Frankenfeld)

Temperature °F.	Progeny of 100 Weevils After 5 Months in Wheat With Moisture Content of						
	8%	9%	10%	11%	12%	13%	14%
70	0	0	0	87	4,827	8,692	10,745
75	0	0	0	0	4,262	9,244	12,444
80	0	0	326	885	9,681	10,267	13,551
85	0	0	0	...	5,090	6,436	5,983
90	0	12	413	984	2,233	3,230	3,934

The lesser grain borer has been observed to breed in 8% moisture wheat at high temperatures. Some interesting curves (Fig. 7) showing the effect of temperatures and grain moisture on the relative speed of multiplication (biotic potential) of populations of the rice weevil (small strain) and the lesser grain borer were published by Birch (11) in 1945. He used a different strain of the rice weevil, and this may account for the fact that no reproduction was obtained in 10% moisture wheat.

Bran beetles are less dependent upon the moisture content of their food supply, for they are able to breed in flour or grain dust from which practically all moisture has been removed. Nevertheless, a high moisture content in grain is much more favorable to their rate of reproduction and survival. The presence of dockage or grain dust is of vital importance. Without it, dry grain is unfavorable for the reproduction of the beetles. The effect of grain moisture on the reproduction of the confused flour beetle is indicated in graphic form in Figure 4. The same figure shows the effect of the presence of various percentages of dockage or grain dust as well as the modifying effect of temperature. At high temperatures the lack of moisture and absence of grain dust are less important to the insect. The effect of grain moisture on the survival of confused flour beetle adults is shown in Figure 8. It is evident that the longevity of the insect is reduced as the grain moisture

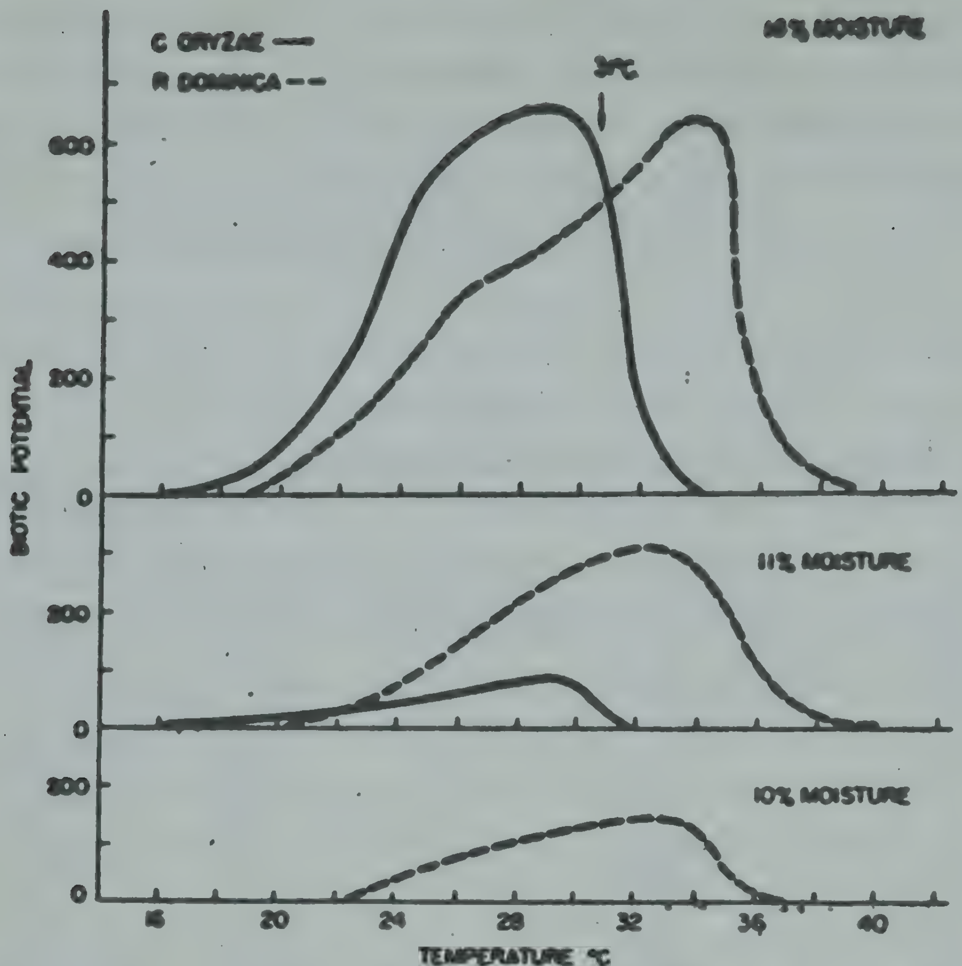

Fig. 7. Showing the relative speed of multiplication (biotic potential) of populations of *Sitophilus oryza* and *Rhyzopertha dominica* over the complete temperature range for these insects in wheat of 14, 11, and 10% moisture content. The vertical arrow shows the temperature above which the biotic potential of *R. dominica* exceeds that of *S. oryza*. (After Birch, 11.)

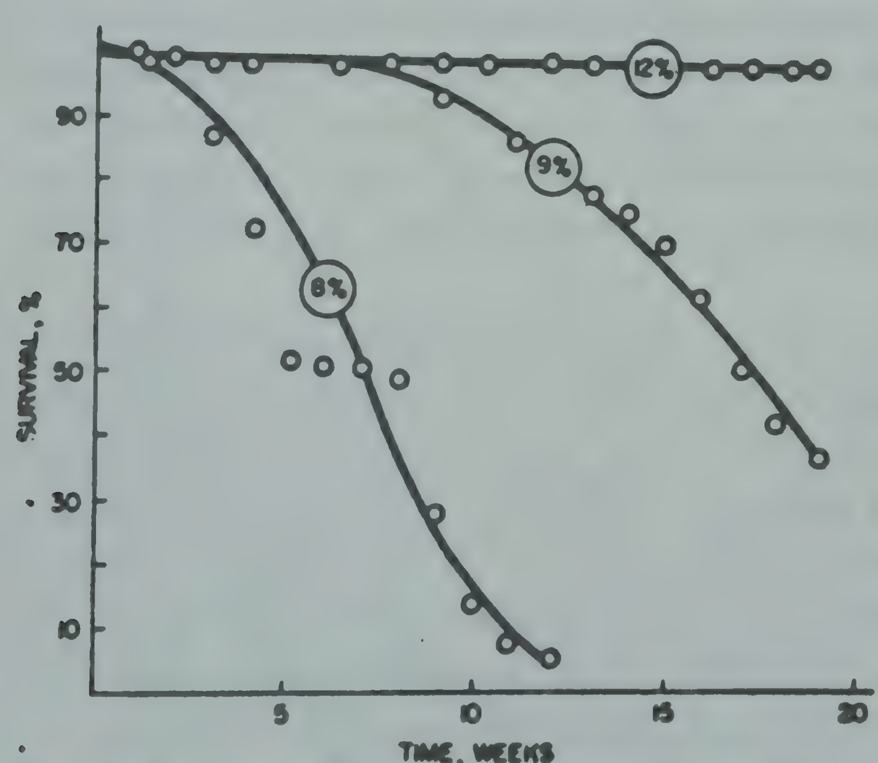

Fig. 8. Survival of confused flour beetle adults at 80°F. in clean wheat of different moisture contents. (Unpublished notes, Cotton and Frankenfeld.)

is lowered, although low moisture has less effect on this species than on the rice weevil. Figure 9 shows how the presence or absence of grain dust in dry grain changes the longevity of the flour beetle.

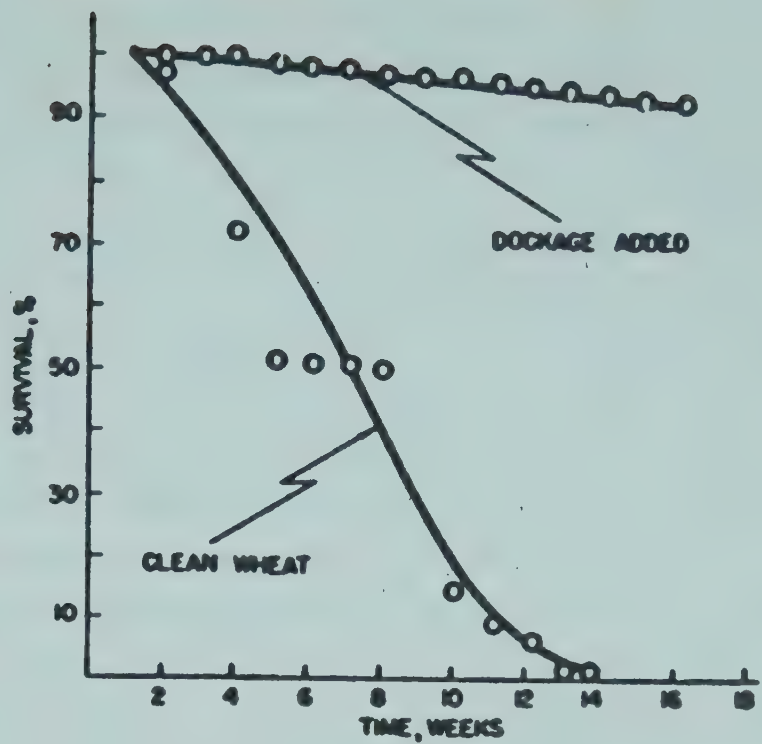

Fig. 9. Survival of confused flour beetle adults in 8% moisture wheat as affected by the presence or absence of dockage. (Unpublished notes, Cotton and Frankenfeld.)

The effects of the moisture content of wheat in farm storage on its attractiveness to insects and on the rate of reproduction of a miscellaneous insect population are indicated by the data of Table IV. Wheat

TABLE IV

COMPARISON OF THE RATE OF INCREASE OF INSECT POPULATIONS IN GRAIN OF DIFFERENT MOISTURE CONTENTS STORED IN WOODEN FARM BINS IN RENO COUNTY, KANSAS[a]

Moisture Class, %	Number of Bins	Mean Moisture of Series, %	Number of Insects per 1000 g. of Grain				
			July	August	September	October	November
8.0– 8.9	12	8.6	0	2.2	13.0	5.5	0.5
9.0– 9.9	29	9.5	2.4	8.5	5.3	4.3	6.2
10.0–10.9	74	10.5	5.9	7.6	7.4	8.7	4.9
11.0–11.9	242	11.5	2.4	11.5	15.4	20.5	9.4
12.0–12.9	211	12.4	6.1	10.8	15.5	30.8	21.8
13.0–13.9	66	13.4	3.1	17.5	40.6	43.4	44.9
14.0–14.9	28	14.4	5.4	37.0	67.7	112.2	31.2
15.0–15.9	4	15.3	6.1	15.0	27.8	3.7	...

[a] Data furnished by H. H. Walkden, United States Bureau of Entomology and Plant Quarantine, Hutchinson, Kansas.

of varying moisture content that was uninfested when placed in farm bins in June was sampled at monthly intervals to determine the relative attractiveness of the various lots of wheat to insects and the rate of de-

velopment of infestation. Insect populations were never excessive in dry grain, whereas in more moist grain insects multipled rapidly. Grain with a moisture content above 15% was attractive to insects at first, but infestations later died out.

Heating of Grain by Insects. Bulk grain with a water content of from 11 to 15% and in apparently good condition except for the presence of insects often becomes hot. Heat production from the metabolism of the grain and of microorganisms under such conditions is not sufficient to account for the rise in temperature but, according to Oxley (39, 40), Oxley and Howe (41), Birch (12), and others, the source of the heat is the metabolism of the insects themselves. A comparatively small number of insects can produce enough heat to cause spontaneous heating. Oxley (40) studied many cases of heating in dry grain and concluded that in every case the cause was insect infestation. In such cases the temperature of the grain did not rise above 108°F.

In large bulks of grain where heat loss to the surrounding atmosphere is not rapid enough to prevent the development of hot spots in the interior of the bulk, the temperature becomes too high for the grain weevils. The adult weevils move to the cooler grain, and the immature stages within the kernels which cannot move are often killed. According to Birch (12), who made studies of large bulks of grain stored in Australia during the war years, the only parts of the bulks where temperatures were sufficiently low for the insects to survive were on the surface and sides, so that the damage was generally confined to a few inches near the surface. The writer has observed that, in small lots of grain, temperatures favorable for weevil development are often maintained throughout the winter regardless of the air temperature.

In bins that are heating as a result of insect activity, surface grain may become caked and damp from translocation of water within the bulk of grain under the influence of a temperature gradient. This is most obvious in the autumn when surface grain cools rapidly and water vapor moving from the heating areas to the cooler grain condenses and causes molding and sprouting. Surface layers of moldy grain are seldom more than from 6 to 8 in. in depth.

In grain with a moisture content above 15%, heating may occur without the presence of insects, and according to Oxley (39, 40) this form of heating is characterized by much higher maximum temperatures than occur in dry-grain heating caused by insects. He considers the microflora on the surface of the grain, perhaps together with bacteria, to be the chief source of the heat produced by damp wheat. He states that, "Although the two types of heating are usually distinct, it is not uncommon for features of both to be combined in a single bulk. This

can occur when the grain is at a water content near the border line between the two types (i.e., about 15–18%) in the following way. Since the rate of heat production increases with temperature it is possible for damp grain, potentially capable of spontaneous heating, to remain cool indefinitely if it is sufficiently cool at the start. In this condition, if insect infestation occurs and develops sufficiently to cause some 'dry grain' heating, the respiration rate of the grain may easily rise to a level at which its heat production is sufficient to maintain and increase the temperature. That is to say, dry grain heating initiates, and is superseded by, damp grain heating, with its characteristic higher maximum temperatures."

Sources of Infestation. Sources of infestation of stored grains are well known. As previously stated, the field infestation of small grains, with the exception of rice, is of little consequence. Most infestation of small grains originates after they are placed in storage. Insects that breed in grain while it is in storage, and then live over in the woodwork of bins from one crop to another, are largely responsible for the infestation of grain stored on the farm or in country elevators. However, infestations in farm-stored grains may frequently be initiated or supplemented by insects that fly or crawl from other nearby sources on the farm, such as accumulations of waste grain or feed, or stores of mill feeds.

Corn grown in the large corn-growing regions of northern United States becomes infested in the same ways. In these regions, with their comparatively short growing season, corn is usually harvested while the moisture content is still high and is stored on the ear in cribs or slat bins so that it will dry safely. Winter temperatures are usually low enough to destroy any field infestation that may have occurred. Normally, this corn is fed before it becomes reinfested. In the southern United States, however, and in countries with similar or warmer climates and a longer growing season, corn is normally left in the field to dry. Under these conditions it invariably becomes infested in the field. Rice is similarly subject to field infestation, which is augmented during the warehouse storage of the bagged rice or during bulk storage in farm bins or in crib bin elevators.

Distribution of Insects in Bulk Grain. The distribution of insects in bulk grain is influenced by a number of factors. If the adult insect is fragile and weak, as is characteristic of the various species of moths that infest grain, it is unable to force its way below the kernels on the surface to deposit its eggs. For this reason, moth infestations are largely confined to the surface grain. Grain-infesting insects of the weevil or bran beetle type are powerful enough to move freely through a bin of grain. The distribution of these insects in bulk grain

appears to be influenced largely by temperature and moisture.

Temperature is perhaps the more important factor. As already mentioned, it was observed by Birch (12) that in bulk wheat stored in piles severe damage was confined to 4 or 5 in. all over the surface and to a depth of several inches on the floor. High temperatures in the middle of the bulk grain, generated by the metabolism of the insects, killed the insects there or drove them to the cooler grain of the surface.

The effects of temperature on insect distribution in wheat stored in small steel bins in the United States are quite pronounced. During spring, summer, and autumn a majority of the insect population of a bin of bulk grain will be found in the upper half of the bin, whereas in midwinter a majority of the insects are likely to be found in the lower half of the bin. In midsummer the insects in the bin are usually uniformly distributed in the four quadrants of the bin, whereas in winter most of the insects will be found in the south quadrant of the bin.

In elevator bins insects are often more abundant at the bottom and in the surface grain, but are likely to be found in any part of the bin. The position of insect colonies in a bin is quite likely to be due to chance distribution in the loading of the bin. In bins equipped with thermocouple cables the distribution of insect colonies is usually indicated by areas of high temperature or "hot spots" in the bin.

Insects are attracted to damp grain. If leaks occur and portions of a bin of grain become damp, insects will always be found in greater abundance there than in the dry areas of the bin. Surface grain that is cooler than the rest of the grain in a bin may become damp as a result of translocation of water. Whenever a mass of grain has parts at different temperatures, there is a movement of water from the hotter to the cooler parts. When heating by insects occurs beneath the surface grain and outside temperatures are low, the temperature gradient is very steep and water movement may be excessive and considerable rotting of the surface grain may result. Damp surface grain often attracts large populations of scavenger insects such as the hairy fungus beetle and the foreign grain beetle.

The Succession of Species. The population complex of insects in bulk stored grain is seldom static for very long periods. The many factors that influence insect abundance cause continual changes in the predominance of the various species throughout the year. In regions where field infestation occurs, the species that fly to the field provide the original insect population. In some regions this field infestation may be restricted to that of the Angoumois grain moth, whereas in others it is likely to include the rice weevil and numerous other species that fly.

The Angoumois grain moth and the rice weevil, through their initial attack, prepare the way for the bran beetles and scavenger insects, some of which, as a result of shorter developmental periods, soon greatly outnumber the original inhabitants of the grain bin. Grain placed in storage in wooden farm bins may be quickly infested by the cadelle, which sometimes migrates from the woodwork of the bins in such large numbers that the surface of the grain may appear to be in motion. The relatively long development period of this insect prevents it from holding its original predominant position in the population complex for very long. Again, as the cool weather of autumn approaches, the cadelle population leaves the grain and enters the woodwork of the bin to hibernate over winter. In the Great Plains area of the United States, infestations of the lesser grain borer in wheat are often accompanied by high populations of the long-headed flour beetle. This may be due to the fact that wheat attacked by the lesser grain borer becomes quite floury. If grain is held in storage over the winter in temperate zones, the hardier species such as the flat grain beetle and the saw-toothed grain beetle survive the winter in greater numbers than the rest. During the spring months these two species are likely to be much more abundant than the others.

Considerations Relating to Cereal Products. The factors that influence the abundance of insects in stored grain also affect their abundance in milled cereal products. In general, as temperatures and relative humidities rise, the rates of reproduction and development increase, although there are upper limits above which both temperature and moisture conditions are unfavorable. Gray (31) observed that the rate of oviposition of the confused flour beetle increased with the rise in temperature, from an occasional egg at 61°F. to an average of 10.1 per day at 90°F. Hatching occurred up to 100°F., but at 105°F. all eggs were dead in 60 hours. Holdaway (35) noted that eggs of this insect did not hatch in a saturated atmosphere, owing to fungus growth. Biotic constants for the confused flour beetle reared on whole wheat flour at a constant relative humidity of 75% and for various temperatures were established by Chapman and Baird (14). They found that at 22°C. (71.6°F.) the average duration of egg, larval, and pupal stages totaled 93.05 days, whereas at 32°C. (89.6°F.) it was only 27.13 days. At 17°C. (62.6°F.) the larvae died before pupating. Holdaway (35) noted that, under constant temperature conditions but with variable relative humidity, the rate of growth of a population of the confused flour beetle increased with the rise in relative humidity from 25 to 75%. Furthermore, he observed that the population that a given unit of flour would maintain increased with the increase in relative humidity. An increase

in population of 20% occurred with a rise in relative humidity from 25 to 50%, and an increase of 58% occurred as the relative humidity rose from 25 to 75%.

The factors of nutrition and the availability of food sometimes operate to modify the effects of relative humidity and temperature. When grain is milled, the food content of the kernel is made available in a form that can be utilized by the immature stages of insects that are unable to breed in undamaged grain or grain with a moisture content below a certain level. Some insects are able to breed in flour from which most of the water has been removed. Fraenkel and Blewett (26) found that the confused flour beetle and the saw-toothed grain beetle developed fairly well in flour at about 6% water content and the Mediterranean flour moth at 1%. In a further publication the same authors (27) showed that the confused flour beetle and Mediterranean flour moth are able to breed in food with little moisture by the utilization of metabolic water. At lower humidities more food is eaten to produce a given unit of body weight, the length of the larval period increases, and the weight of the pupae decreases. More food is eaten at low humidities because part of the food is utilized as water. For every milligram of dry weight of pupae produced, the confused flour beetle consumed an average of 5.17 mg. of food (dry weight) at 70% relative humidity and an average of 7.25 mg. at 20% relative humidity. Some insects do not grow well in flour with a water content below 10%. With flour in equilibrium at 90% relative humidity, the growth of molds prevents development of insects.

The food medium greatly affects the rate of reproduction and the rate of development of insects. Cotton, Frankenfeld, and Bayfield (17) found that the enrichment of flour with riboflavin increased the rate of reproduction of the confused flour beetle by 72.5% over that in nonenriched flour, and that the beetle reproduced faster and developed more rapidly in shorts, bran, and whole wheat flour, which are naturally rich in this vitamin, than in clear, straight, or patent flours.

A considerable amount of research work has been done on the basic vitamin requirements of the confused flour beetle and other insect pests of stored cereals by Fraenkel and Blewett (26). According to these writers, all insects require vitamins of the B group, and at least seven of this group are essential for the proper growth and development of the flour beetle. These are: thiamine (B_1), riboflavin (B_2), nicotinic acid, pyridoxine, pantothenic acid, choline, and biotin and possibly also inositol and p-amino-benzoic acid. According to these authors, some stored-product insects have lower vitamin requirements than others, possibly owing to the presence in their bodies of intracellular micro-

organisms or symbionts that provide accessory food substances. The flour beetle does not possess these intracellular symbionts.

Insect infestations in bagged cereal products tend to concentrate near the outside layers. Studies of flour in warehouse storage have shown that with flour beetles about 95% of the population will be found in the outer 4 in. in a 100-lb. bag of flour. Flour beetles placed in the center of 100-lb. bags of flour have also been observed to move to the outer layers of flour, and examination of the flour in the center of infested 100-lb. bags will show few if any dead insects. This would indicate that the insects found there have wandered from the outer layers.

Similar observations have been reported for the saw-toothed grain beetle and other beetles. The larvae of moths invariably come to the outside walls of bags to pupate.

The crowding of insect infestations in the outer layers of bagged milled cereals may restrict the growth of insect populations; Chapman (13) has shown that in a given quantity of flour a confused flour beetle population soon reaches a condition of relative stability beyond which it does not increase. At a constant temperature of 27°C. and a uniform moisture content, he found that the mean number of individuals, per gram of whole wheat flour, when populations reached equilibrium was 43.97 with a standard deviation of 4.27 and a probable error of 2.88. The consumption of eggs by larvae and adults is the limiting factor in the growth of such populations.

Heating of cereal products as a result of insect infestation occurs at times but is not so common as the heating of grain. The fundamental causes of heating and the reactions of the insects are much the same in both cases.

Damage Caused by Insects

The actual damage caused to stored grain by the direct feeding of insects is difficult to estimate. Such information as is available is summarized in the following two subsections which deal respectively with grain and cereal products.

Damage to Grain. In farm storage where the greatest losses are sustained, little grain is actually weighed when it is placed in bins so that it is impossible to determine accurately the shrinkage due to insect feeding during storage. Hinds (33) has published the results of a careful study of weevil damage to corn stored in central Alabama in 1912. He estimated that one-half of the corn stored up to April, and all after that, suffered a loss valued at 5 cents per bushel per month. With the average value of corn at 55 cents per bushel in 1912, this would represent a loss of approximately 9% per month. The actual loss to

farm-stored wheat in years of severe infestation, due to actual feeding by insects, has been found to amount to 1% per month from July to November.

The type of infestation has a marked effect on the damage caused by feeding. Many bran beetles, mites, and surface-feeding moth larvae feed principally on the germ, destroying germination and a high percentage of the most nutritive portion of the grain. In 1946 Richards and Waloff (44) reported that one larva of *Ephestia elutella* (Hübner), during its development, consumed 47.7 embryos of Manitoba wheat. Fraenkel and Blewett (26) recorded the average number of kernels of grain damaged by one larva during its development for seven different species of insects. The data taken from their own experiments and work published by other authors show that some of the abundant grain-infesting species that are not generally considered as prime destroyers of grain actually cause considerable damage by devouring the germ.

Weevils and flour beetles are prime destroyers of the endosperm. According to a paper published by Richards (43) in 1947, a rice weevil larva turns about 14 mg. of a grain into carbon dioxide and water and produces 14 mg. of frass while developing into a weevil weighing 2.4 mg. About two-thirds of the endosperm of a kernel of wheat is consumed by a weevil.

Heating and spoilage of grain due to the presence of insects often results in damage far greater than that caused by their feeding. This is particularly true of bran beetle infestations. Many observations of bins of shelled corn in Iowa that were heating due to bran beetle infestations revealed that the serious damage was confined to 6 or 8 in. of surface grain; this rotted and spoiled as a result of the condensation of water vapor transferred from the heating area to the cool surface. In other cases, heating initiated by insects in high-moisture wheat, and carried on by microflora and bacteria, has frequently been observed to result in temperatures high enough to cause "bin burn."

The presence of an appreciable percentage of insect infestation within kernels of wheat seriously reduces its value for milling purposes. Free living insects can be removed from wheat by appropriate cleaning machinery, but the insect stages concealed within the kernels are difficult to eliminate. The most promising method of removing insect remains and filth from milling wheats is to run the tempered grain through an Entoleter scourer-aspirator. The kernels weakened by insect feeding are broken by centrifugal force and the insects and their filth removed in part by scouring and aspiration.

Damage to Cereal Products. The presence of insect infestation or insect contamination in milled cereal products intended for human con-

sumption is much more serious than it is in stored grain. There are no practical methods of removing all insect contamination from such products, and in the United States such infested cereal products entering into interstate commerce are subject to seizure and destruction or diversion into feed. The actual destruction of milled cereal products by insects is of minor importance in such circumstances.

That the amount of food consumed by insects is considerable is indicated by the observations of Crombie (21). He reported that the average weights of flour consumed per week by larvae, during development, and by an adult male and female were 6.75, 2, and 2.25 mg. for the saw-toothed grain beetle, and 26, 2, and 3 mg. for the confused flour beetle. Considering the estimate of Gray (31) that the progeny of two confused flour beetle adults could amount to over a million in 150 days, an undisturbed infestation of flour beetles could consume a large quantity of flour in a relatively short period.

In addition to the actual flour consumed, a disagreeable, pungent odor given off by the scent glands of flour beetles is often imparted to flour, giving it a disagreeable taste and odor.

Moth larvae have the habit of spinning silken webs over foodstuffs so that the fouling of cereal products ruins even more than the actual quantity eaten. The Mediterranean flour moth and the Indian-meal moth are notorious for this type of damage.

In addition to the damage they cause by feeding on and infesting bagged cereal products, spider beetles, the cigarette beetle, *Lasioderma serricorne* (F.), and the drug-store beetle, *Stegobium paniceum* (L.) weaken the bags by cutting holes in the fabric so that stacks of badly infested products may collapse. Freeman and Turtle (29) state that flour infested with mites has a "minty" smell that is particularly objectionable. When such flour is used for breadmaking, the bread has a sour taste, poor color, and may not rise adequately. According to the same authors, wheat offals, particularly bran, may suffer a reduction in weight up to 10% as a result of mite attack, and with the concomitant mold development the material may become heated, sour, and lumpy, and unpalatable to livestock.

Cereal products shipped in infested railway boxcars are often found to have a few insects crawling over the bags on arrival at destination. Although the infestation may not have penetrated the bags, the consignee will assume that the shipment is infested, with the result that fumigation of the shipment will be required at the very least. If serious contamination of the product has occurred, the loss will be greater and a portion or all of the shipment may have to be diverted to feed.

If badly infested wheat is used for milling, the insects and insect

excrement within the berries will be ground up in the milling process and will add materially to the insect fragment count of the finished flour. Insect excrement and small insect fragments cannot be removed from flour by any practical method, so that flour made from badly infested wheat is of value only for feed.

The same thing holds true in the manufacture of corn meal from insect-infested corn. Furthermore, the simplified method of milling corn employed in many small mills is inadequate to remove or destroy all of the insect eggs and small larvae, so that heavy infestations may develop soon after the meal leaves the mill.

The custom of using clear and low-grade flours to make special mixes for bakeries may cause considerable damage to cereal products. These flour stocks are usually purchased and are often infested. If they are not processed to remove insect life before blending, and if they are mixed with other flour just before it reaches the packer, the entire batch may become infested. The presence of insect excrement and insect fragments in such flours may serve to contaminate the finished product even if no insect life is present.

Self-rising flours prepared at wholesale groceries in the southern states are frequently damaged by insects. Flour-blending equipment in such establishments often consists of a mixer for adding salt, phosphate, and soda to the flour, and a small sifter for screening out large lumps, insects, and other foreign matter. A 20-wire screen commonly used in such sifters will remove adult flour beetles but is too coarse to take out eggs and young larvae. Flours purchased for this purpose are often low-grade and particularly susceptible to insect infestation, and by the time they are mixed they are quite likely to be infested. Since the eggs and small larvae are not removed during the mixing process, the self-rising flours produced are likely to develop heavy infestations if kept on hand very long.

Supplies of malt are frequently infested by insects. When malt is added to flour, the resulting damage may be serious unless the finished flour is treated to destroy infestation.

Animal feeds are more attractive to insects than the more refined cereal products. They are seldom given adequate treatment during manufacture to destroy all infestation, so that they are a constant source of infestation to other cereal products.

Damage to cereal products from moths and beetles is most severe when they are packaged in fabric bags. Beetles lay their eggs directly through the meshes of the fabric or through needle holes along the seams or where the tops are sewed. Paper bags offer more protection, but poor sealing allows immature stages of moths and beetles and small

species of beetles to enter the bags with ease. The same thing holds true for cardboard fiber packages where the shell is printed and the ends sealed with adhesive. The ends are never sealed sufficiently to exclude insects.

Detection of Insect Infestation

Frequent inspection of grain stocks in all types of storage is desirable in order to discover incipient infestations before they have a chance to become serious. In temperate climates during the warmer months and in warm climates throughout the year, it is recommended that inspections be made every 2 weeks of stocks that have been in storage a month or more. The inspection should be sufficiently thorough and should be conducted in such a manner as to indicate what pests are likely to be encountered in the area.

Stored Grain. Surface infestation of moths such as the Indian-meal moth may be detected in elevator bins by examining the walls and ceiling and the surface of the grain for the presence of moth larvae and webbing. Another good indication of pests of this type is the presence on the surface of the grain of kernels from which the germ end has been removed. In bagged grain, webbing and other signs of the presence of moth infestation are visible on the outside of the bags.

Infestation in small grains in farm storage is usually found in the top half of the bin during periods when grain temperatures are above 70°F., and the sifting of samples of the surface grain will often serve to determine whether or not serious infestations are present. During the winter, infestations are likely to be nearer the center of the bin. Grain probes are needed for obtaining representative samples from the interior of the mass of grain. To facilitate this type of inspection, bins should be provided with roof hatches or removable ventilators unless they are so constructed as to allow head room enough for using grain probes.

The temperature of the grain is often a good index of its condition both in farm and commercial storages. In commercial grain storage, especially, every effort should be made to take temperature readings regularly. Many elevators are equipped with thermocouple systems by which the temperature at various points in a bin may be taken, and readings quickly and accurately recorded. When dead storage is necessary, temperature readings may be taken by means of a system of pipes and thermometers. Although not so accurate as the thermocouple system, this method does indicate the conditions at the point where the pipe is installed. Sample probes containing a thermometer also give a fairly accurate picture of the temperature conditions at the point sam-

pled. Rods inserted in the grain in farm bins and later applied to the hand, and the insertion of the arm itself in shallow bins, can be used to obtain approximate grain temperatures.

Where temperature is used as a criterion of grain condition, records taken at regular intervals are necessary. A temperature of 80°F. may be normal and safe in one bin, while 70°F. in another bin under different conditions may indicate the beginning of a dangerous infestation. The actual temperature is not so significant as any sudden increase in the temperature which cannot be explained. For instance, a rise in temperature in a week from 67° to 70°F., in a bin center at a point 20 ft. below the surface in undisturbed elevator grain, is not a very great change. However, if this point shows a temperature of 73°F. the following week, the bin should be examined thoroughly without delay.

Where temperature records are not available and heating or deep-seated infestation is suspected, the grain should be drawn off and examined. If this is not possible, a number of representative samples should be taken by probing. Multiple-sample probes have recently been developed by which a bin can be sampled at different depths down to 75 ft. or more in a single operation. A multiple-sample probe described by Anderson and Martin (3) in 1943 is made in 3-ft. sections. The bottom section takes the form of a large auger which is turned into the grain by means of a T-handle. Three-foot standard sections are then added and turned down with the handle, one after the other, until the probe reaches the necessary depth. When the handle is turned counterclockwise all sections open to take samples.

Patches of "tough" grain on the surface of a bin or pile are often associated with high temperatures and insect infestation some distance below the surface. Tough grain, either at the surface or at the bottom of a bin, is a frequent accompaniment of grain mite infestation. When this pest is present in dangerous numbers, there is usually a sickly sweetish odor about the grain.

A method of determining the presence of dangerous quantities of hidden infestation in grain was described by Howe and Oxley (36) in 1944. The method depends on the fact that insects, though never more than a very small fraction of the total weight of the grain sample, give rise to a very large proportion of the total carbon dioxide which the sample produces. A uniform sample of grain is taken by standard procedure and is sifted to remove free living insect forms. The grain is then incubated for 24 hours at 25°C. (77°F.). The concentration of carbon dioxide in the interstitial air is then estimated by a gasometric method accurate to plus or minus 0.2%. The concentration obtained is known as the carbon dioxide figure. A correction can be made for

the effects of variations in the intergranular air space according to the type of grain being tested.

If the carbon dioxide figure exceeds 1% it is certain that a potentially dangerous insect infestation is present. A figure of 0.3% may represent insect-free grain if the moisture content of the grain is 14% or above. If the moisture content is below 14%, such a reading would indicate a slight infestation. A reading of between 0.3 and 0.5% indicates either a slight insect infestation or a moisture content higher than 15%. A figure between 0.5 and 1% indicates that the grain is unfit for prolonged storage.

A more rapid method of detecting the presence of weevil infestation within grain was described by J. C. Frankenfeld (28) in 1948. This method is particularly valuable to millers in that it indicates the presence of insects, whether they be dead or alive. Chemicals are used which stain the gelatinous plugs secreted by the weevils in sealing their eggs in place in the grain kernels, or which color the pieces of endosperm adhering to the egg plug or exposed by insect feeding or mechanical injury. The solution considered most useful is made by mixing 50.0 ml. glacial acetic acid in 950 ml. of distilled water and adding 0.5 g. acid fuchsin. Uniform samples of grain prepared by soaking in warm water for 5 minutes are immersed in the stain for 2 to 5 minutes, after which the excess stain is removed by washing the samples in tap water. The acid fuchsin stains the gelatinous egg plugs a deep cherry red, while feeding punctures and the results of mechanical injury are stained a light pink. The egg plugs are about the size of an ordinary pin prick and can be readily seen with the naked eye. However, the use of a reading glass is helpful. This stain is useful for detecting infestation in wheat, corn, or sorghum. Other stains have been suggested for staining weevil egg plugs in wheat but have not come into general use.

A more positive method of detecting internal insect infestation in grain was proposed by Milner *et al.* (37a) in 1950. X-ray apparatus is used to take radiographs of grain samples. These radiographs reveal the presence of insect forms within the kernels.

A rapid method of estimating the internal insect infestation in a grain sample is based on the assumption that for every kernel of wheat with a weevil emergence hole, there are five times that many kernels with internal infestation. To quickly detect the number of kernels in a sample with weevil emergence holes, Apt (4a) in 1952 suggested a flotation technic whereby a 100-g. sample of wheat is placed in 2% ferric nitrate solution, made by adding 2 g. of hydrated ferric nitrate to 100 ml. of water. After 30 seconds' agitation of the sample to wet the kernels, those with weevil-emergence holes will float and can be counted.

Cereal Products. The presence of insects in milled cereal products can be readily detected in the case of heavy infestations, but this is more difficult when the infestation is light.

Moth infestation should be suspected if adult moths are seen resting on the walls of storage warehouses during the day or in flight at dusk. Webbing over the bags or the presence of cocoons on the exterior of the bags indicates serious infestation of the cereal products.

If beetles are involved, the adult insects are usually to be found between bags in a stack or underneath individual bags. If there are light deposits of dust on the floor around stacks of bagged cereal products the presence of insects is revealed by tracks in the dust.

Infestations originating in storage will be found in the outside bags of a stack. The sifting of samples taken from bags on the outside of stacks in various parts of a warehouse will reveal the presence of light infestations. The sifting of flour through a No. 64 wire screen will remove most of the eggs, larvae, and other stages of insects.

Flour used in blending operations, in mixes, or specialty products should always be examined, for the presence of both insect infestation and insect contamination. The presence of living infestation can be determined by sifting. Four or five bags taken at random from each carload of flour should be sifted.

Examination of Milled Cereals for Insect Fragments. For the detection of insect fragments in milled cereals, which may be present but are not detectable by macroscopic examinations, procedures have been published by the Food and Drug Administration (48), the Association of Official Agricultural Chemists (5), and the American Association of Cereal Chemists (1, 2). Recommendations relative to useful procedures for the examination of food products for extraneous materials that will also be found helpful to analysts are contained in the Report of the 1945–46 Committee of the New York Section of the American Association of Cereal Chemists (51).

Essentially, the process consists of digesting the sample with pancreatin or hydrochloric acid, making gasoline or light mineral oil separations of the extraneous material, and identifying the separated material. Harris and Knudsen (32), in reporting on the efficiency of various filth recovery procedures, describe the two procedures in common use for detecting insect fragments in flour as follows:

Digestion in pancreatin solution: Weigh 50 g of flour into 250 ml beaker. Add ca 60 ml pancreatin soln (prepared as a filtered aqueous extract of 5 g pancreatin per 100 ml H_2O) and stir into smooth paste. Add ca 40 ml of the pancreatin soln (100 ml total) and mix. (Adjust to *p*H 7–8 with ca saturated Na_3PO_4 soln). Allow to stand ca 15 min., and if necessary readjust to *p*H 7–8. Maintain at 40° for not less than 3 hours. Transfer digested material to liter Wildman trap flask. Add 20 ml of gasoline and

mix thoroly. Allow mixture to stand 5 min., fill with saturated NaCl soln, and after 30 min. trap off into 250 ml beaker. Add ca 10 ml gasoline to the material in the trap flask, stir the gasoline into the mixture and after ca 5 min., trap off into the same beaker. Transfer contents of beaker to trap flask and fill with saturated NaCl soln. Stir and after ca 30 min. trap off into beaker and filter thru rapid filter paper, using suction. Examine microscopically.

Digestion in 400 ml 2% hydrochloric acid: To 50 g flour in a beaker add water and stir in a thin smooth paste. Add H_2O to make 400 ml total H_2O added. Add conc. HCl to make total HCl of water 2%. With intermittent stirring bring to a boil and boil 20 min. Transfer to 2 liter trap flask and trap off with gasoline and water in the usual manner.

In commenting on the above procedures these authors concluded: that the use of water in the trapping procedure gave significantly higher recoveries than did the use of salt solution, that a second "trapping off" recovers additional filth elements, and that the average insect fragment count using large quantities of dilute hydrochloric acid was as high as or higher than any of the averages for pancreatin digestion.

For the detection of insect excreta in flour the following method given in *Methods of Analysis* of the Association of Official Agricultural Chemists (5, p. 715) will be found useful:

Weigh 0.20 g of flour on tared, flat, glass disk of 7–7.5 cm diam. Add clove oil and spread mixt. into thin uniform layer. (There should be sufficient oil present to clear flour and present smooth surface of oil, but not so much that mixt. will flow off disk.) Place wire grid over disk and examine microscopically with dark background and intense reflected light.

Prevention and Control of Infestation in Grain

The question is frequently asked, "What constitutes a dangerous infestation in stored grain?" The discovery of living insects in bulk grain should always be looked upon with suspicion. However, the need for action will depend upon circumstances and the particular insect involved. In general, if living specimens of the rice weevil, granary weevil, or lesser grain borer are present, or if in their absence, there are sufficient bran beetles present to cause heating, the situation is dangerous and calls for immediate application of control measures. Similarly a surface infestation of moths is dangerous. The presence of a few bran beetles in stored grain toward the end of the warm season when the grain is cooling normally is probably not serious. The grain involved should be kept under observation to see that no important changes occur.

Farm Storage. Preventive measures are most important in the protection of grain and its products from insect damage. It is essential that clean, insect-free, and weatherproof storage be provided on the farm and that nearby sources of insect infestation be eliminated. Good house-

keeping is the simplest and best preventive measure. Insect pests require food to carry them over between crops. It is difficult for them to establish and maintain themselves in premises that are always clean and free from accumulations of grain, cereal material, dust, and debris. If possible, steel bins that are easy to clean should be used for farm storage. When wooden bins are employed, they should be thoroughly cleaned, and as long as possible before they are refilled, they should be sprayed with a 2½% DDT spray at the rate of 2 gal. per 1,000 sq. ft. of wall or floor surface area. This spraying will kill most of the insects that emerge from burrows and cracks in the woodwork. Preventive and control measures differ somewhat for such crops as corn and rice, but are similar for wheat and other small grains.

In regions where field infestation by the Angoumois grain moth occurs, prompt harvesting of wheat and other small grains is essential after the grain is mature. The soft-bodied moths are unable to make their way below the surface of binned grain. Fumigation of all small grains in farm storage within 6 weeks after harvest will normally prevent serious insect damage throughout the remainder of the year.

Corn merits separate discussion. In the southern portion of the United States and other countries with warm climates, field infestation of corn by weevils, moths, and other flying insects is extensive. It can be greatly reduced by planting varieties with long tight shucks, by destroying sources of infestation in the proximity of cornfields, by planting and disposing of early trap crops, by harvesting as soon as the corn is dry enough to store, and by disposing of ears with exposed tops or damaged shucks. If corn is shucked before it is stored, the presence of infestation can be more easily seen. After ear corn is placed in storage it should be fumigated promptly and inspected at monthly intervals thereafter. When reinfestation is observed the corn should be refumigated.

In the commercial corn area of the United States, field infestation of corn is not important since low winter temperatures will kill out infestation in corn stored in cribs. If corn is to be fed during the season, no control measures are necessary. If it is to be stored for an additional season, it should be shelled as early in the summer as possible. After shelling, the corn should be carefully cleaned, and breakage of the kernels should be held to a minimum during subsequent loading operations through the use of proper loading machinery. The use of blowers to fill the bins should be avoided. With good cleaning equipment and properly designed elevators it is possible to place corn in storage with less than 0.5% of cracked kernels.

Spraying the surface grain with petroleum oil at the rate of 2 qt.

to each 1,000 bu. is an excellent preventive measure against infestation by the Indian-meal moth and other insects that are likely to migrate to the bins during the summer. The oil should be either technical white or other refined oil of 100 to 200 seconds viscosity (Saybolt, 100°F.) and should be free from objectionable odor. Shelled corn should be inspected at monthly intervals during periods when air temperatures are above 70°F. and fumigated if found to be infested with weevils or if there are sufficient bran beetles present to cause heating.

Rice commonly is infested in the field by the rice weevil, Angoumois grain moth, and other insects. To reduce this field infestation, sources of infestation must be eliminated. Nearby warehouses should be cleaned thoroughly. All old grain, feed, and sweepings should be disposed of or fumigated before the new crop of rice heads. Strawstacks should be disposed of by spreading the straw on stubble fields or by utilizing it in any possible way.

In the more humid rice-growing regions, the rough rice is stored in sacks in warehouses or, if dry enough, in bulk in farm bins. In the more arid rice-growing regions, the rice is usually combined and stored in bulk. The same need for good housekeeping methods in the care and preparation of storages, described for other small grains, also applies to rice storage. After rough rice is placed in storage it is desirable to fumigate it as soon as possible.

Milled rice is usually stored in 100-lb. packets or bags in warehouses. Ordinarily if new-crop rice is stored in a clean warehouse, one fumigation about midsummer is sufficient provided there is no reinfestation from outside sources. If rice is carried over from one season to another, an early summer and a fall fumigation are desirable. A detailed discussion of the prevention and control of the insect infestation in stored rice was published by Balzer and Cotton (8) in 1947.

Elevator Storage. Grain stored in elevators is more easily cared for than that stored on the farm. The modern elevator is well equipped to handle grain and to treat it by means unavailable to the farmer. Good housekeeping methods in the terminal elevator are just as valuable and necessary as they are in the simplest of farm storages. Grain elevator bins should be cleaned regularly. When concrete bins are neglected, a heroic treatment with wire brushes and heavy brooms is required to remove old grain lines, webbing, and grain debris. This treatment is usually carried out in spare time (largely in the winter time in Canada and northern United States). The grain level is dropped a few feet to expose the caked material and a tarpaulin is placed on the surface of the grain to catch the infested material. Following a thorough cleaning, a routine sweeping of the bins as the grain is withdrawn will

maintain the surfaces in excellent condition.

Bin hoppers vary considerably in design, but very few of them drain entirely clean. The bin bottoms should be thoroughly cleaned periodically to eliminate accumulations of weevils, grain mites, etc. This cleaning not only eliminates many insects but also renders the use of contact insecticides more effective where their use is indicated.

The area above the bins is another place in an elevator which should be gone over carefully. Insects such as the Indian-meal moth leave the bins in large numbers prior to pupation and crawl into cracks and crevices above the bins. The bin floor, manhole covers, tripper, tripper tracks, roof supports, side walls, and the ceiling should all be examined for the presence of insects, and cleaned if necessary.

The foregoing remarks apply particularly to the silo type of elevator with concrete, tile, or steel bins. Those of crib construction are much more difficult to clean and by their very nature afford many more hiding places for insect pests. It is equally important that they be thoroughly cleaned at frequent intervals, if infestation is to be avoided.

In many elevators the grain is turned periodically. This operation consists in moving the grain from one bin to another, and an opportunity is afforded to sample or examine the grain while it is being transferred. If this operation is carried out slowly in cold weather, it will break up any "hot spots" and reduce the temperature and, to a limited extent, the moisture content of the grain. The process tends to retard heating and slows up insect activity where the temperature of the grain is lowered, but it will not eliminate insect problems. Temperature changes observed by Robinson (45) in a bin of wheat turned during cold weather are indicated in Figure 10.

Ordinarily, when the grain stored in a silo type bin is drawn off, the grain at the bottom is withdrawn before the bin starts to "cone" or "core" through the folding in of the surface layer. This has a very definite bearing on insect problems, as infestations of weevils or grain mites are likely to be transferred intact from the bottom of one bin to that of a new bin. Where grain mite infestations occur, they may be readily eliminated by opening the valve of another bin of really dry grain on the same belt so that the tough or mite-infested grain is diluted with several volumes of the drier grain. The dry grain absorbs moisture from the damper kernels thus reducing the percentage of moisture in the entire mass, and the mites soon die in the unfavorable environment.

Grain infested with surface pests such as the Indian-meal moth should *not* be turned. Most of the damage caused by this pest is restricted to the top 3 or 4 ft. of grain. If the bin is turned, the surface grain is mixed with the top third of the bin, new grain is exposed to attack, and the

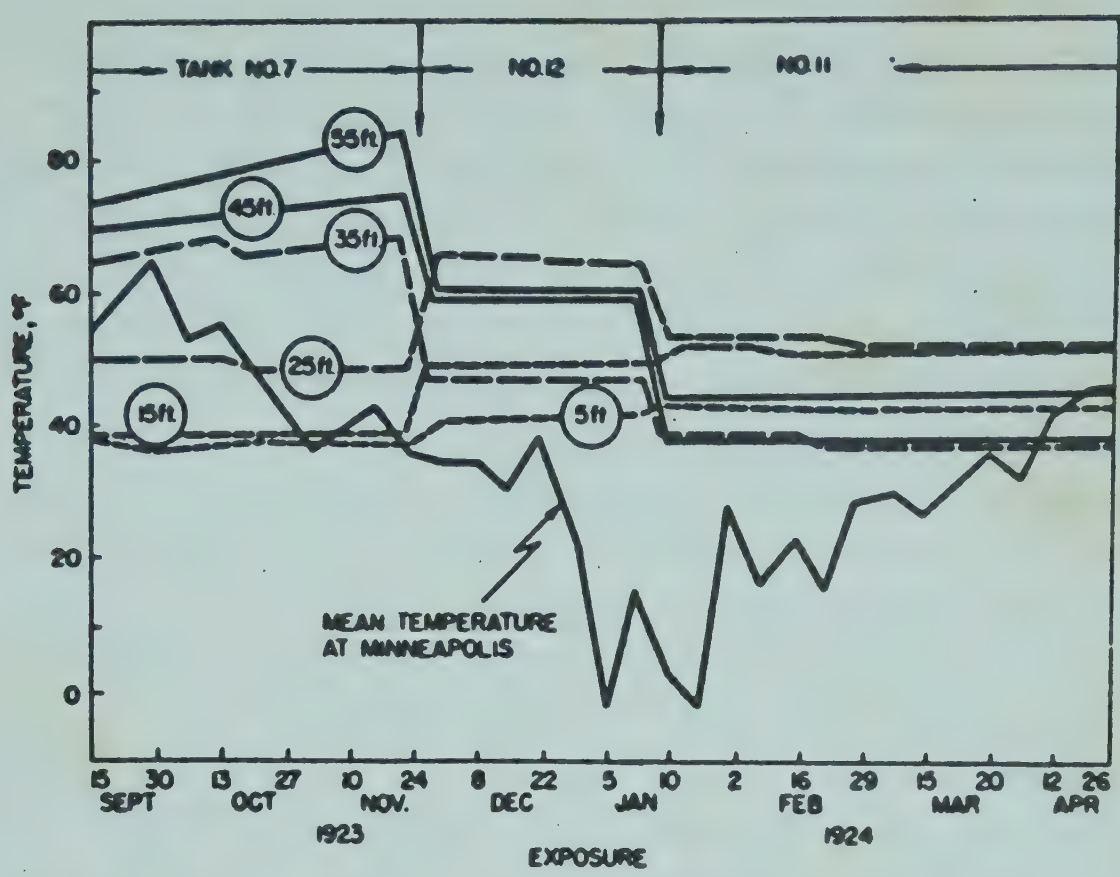

Fig. 10. Temperature changes in a 60-foot bin of wheat at Minneapolis, Minnesota, resulting from transferring the grain twice from one bin to another during periods of low temperature. (After Robinson, 45.)

amount of damage is increased. It is much better to kill the insects and remove the webbing and damaged material before the bin is drawn.

Where pests such as the lesser grain borer are present, turning and cleaning the grain is not only of no value in control but actually aggravates the situation by dispersing the insects. However, less fumigant is required for the fumigation of grain that has recently been turned and cleaned.

Sack Storage. In Australia, India, South America, certain sections of the United States, and many other countries, there is considerable storage of grain in sacks. This type of storage is useful where elevator storage is scarce or lacking, and where small lots of grain are brought together for shipment to commercial centers. Stacks of bagged grain may be left in the open or in temporary depots at railway sidings awaiting shipment, or they may be stored in warehouses, small mills, or in a variety of situations.

In the care of bagged grain in farm or warehouse storage, the same general directions for the care and storage of bagged rough rice will apply. More detailed information regarding good warehouse management is given in a later section.

According to Davidson (22), when grain is to be stored in depot stacks for any length of time, areas should be selected for the stacks that are well drained and free from material that might harbor insects.

The areas should be surrounded with walls of smooth, galvanized sheet metal high enough to keep out rodents. The bags should be stacked on dunnage in orderly piles and roofed over with sheet metal to protect from the rain. A clearance of about 3 ft. should be left between the rodentproof wall and the face of the stack. Side curtains of sacking will protect the stack from driving rains. In filling such depots, care must be taken to see that no infested grain is placed in the stacks. Floors of sheds and dunnage can be sprayed with a DDT-oil spray as a precautionary measure.

Bagged grain in warehouse storage can be fumigated by treating the warehouse as a whole with methyl bromide or individual stacks can be fumigated under tarpaulins. If necessary, depot stacks can be walled in with materials that are reasonably gastight and then fumigated with any good grain fumigant suitable for surface application.

Underground Storage. Underground storage of grain has been employed in many countries and is still popular in many parts of the world. Deterioration of grain from dampness is usually the greatest hazard in this type of storage, although some insect damage may occur if infested grain is placed in storage or if old storages containing infested material are not properly cleaned. It is essential to store only dry, insect-free grain.

According to Attia (6), grain is sometimes stored in Egypt in sand ditches in rainless regions. If the grain is dry it keeps well and remains free from infestation. In some sections of Egypt, bins are excavated in the soil and floors and walls lined with mud mixed with chaff. The floors and walls are also lined with straw as the bins are filled. This type of storage is also common in India according to Fletcher and Ghosh (25) and Janjua and Nasir (37). The latter authors also describe the use in India of cemented underground storages. Subterranean storage in concrete tanks is practiced extensively in Argentina. The underground silos resemble large swimming tanks with ramps at either end to facilitate emptying. Their average capacity is about 21,300 bushels. The filled silo is covered with canvas, on top of which earth is placed, or with a special type of waterproof covering.

Underground storage when tightly sealed has many of the attributes of hermetic sealing. Dendy (23) reported that insects confined with grain in hermetically sealed receptacles die as soon as the oxygen is exhausted and a corresponding quantity of carbon dioxide develops. Vayssière (49), recently urging the more extensive storage of foodstuffs in hermetically sealed containers, stated that hermetic storage causes the death of insects in the foodstuff, forestalls the entrance of rodents and insects, and forestalls the absorption of atmospheric moisture. However,

Oxley (40) warns that in addition to the attractive features of airtight storage, there are certain disadvantages. While accumulation of carbon dioxide in hermetically sealed grain depresses metabolic activities and will ultimately kill insects and rodents, it causes anaerobic respiration of the grain tissues and encourages anaerobic microorganisms. He further states that anaerobic respiration of grain tissue is likely to lead quickly to its death. Such storage would not be suitable for seed grain and is not recommended where the water content is high. He concluded that for ordinary purposes, the provision of special airtight or semiairtight bins for storage of dry grain seems unnecessary and the trouble and expense would not be justified.

Bulk Storage. The piling of grain on the ground or on the floor of buildings is one of simplest methods of grain storage. This method is mainly resorted to in times of emergency when other storage is unavailable. In the Great Plains region of the United States in years of high production, thousands of bushels are stored on the ground and may be left without protection from the weather for several months. In Australia during the last war-period large bulks of grain were stored in bulk depots, while in Canada bulk grain in two million-bushel lots was stored in annex sheds. This type of storage is used in the United States to some extent as permanent storage. In Germany concrete buildings several stories high are used for storing bulk grain. The grain is piled on the floors to a depth of about 6 ft. and is held by bulkheads 3 ft. from the side walls.

According to Attia (6) the *shouna* system of storing grain in piles or stacks surrounded by walls or fences is one of the chief methods of storing grain in Egypt and has been handed down from the ancient Egyptians practically without change. The piles of grain are subject to damage from rain and from the attack of insects, birds, and rodents.

Bulk stored grain is difficult to handle under any conditions, and can be successfully cared for only when it is properly protected from the weather. Surface infestations can be controlled by sprays or fumigants and deep-seated infestations by spot fumigation.

According to Evans (24) the application of mineral dusts to provide a protective barrier over the exposed surface of the bulk grain proved of great value in Australia. Magnesite (ground so that a fairly high percentage would pass a 200-mesh sieve) was found the most reliable of the materials tested, when scattered on the surface of the grain at the rate of 35 oz. per sq. yd.

Contact Insecticides and Aerosols. Both contact insecticides and aerosols are effective against insects such as the Indian-meal moth which cause surface infestations. Extract of pyrethrum (total pyrethrins not

less than 0.8%) in a high-grade oil carrier is a very satisfactory contact spray when applied by means of an electric sprayer. It should be applied at the rate of approximately 6 oz. per 1,000 cu. ft. of space above the grain in closed-top bins. The dosage should be increased to 8 oz. in open-top bins.

Excellent kills are obtained with pyrethrum aerosols when used at the rate of 1 to 1.5 oz. per 1,000 cu. ft. of space above the binned grain. Specially refined pyrethrum is used, and the aerosol usually contains approximately 5% of pyrethrum. Freon 12 under pressure disperses the pyrethrum which remains in the air as finely divided solid particles.

The contact spray and aerosol method of controlling surface infestation is both cheap and effective. The principal drawback is the necessity for repetition at frequent intervals, as the toxic material can only reach those insects which are at or above the grain surface. Persistence in treatment, particularly when the larvae come to the grain surface prior to pupation, will control pests such as the Indian-meal moth.

Surface treatments of farm bins with sprays are useful in preventing invasion of grain by migrating insects. A spray concentrate containing 10% piperonyl butoxide, 1% pyrethrins, and a suitable emulsifier can be applied to the surface grain in a dilution of 1 to 9 with water. This is relatively nontoxic to warm-blooded animals and acts as a repellent to grain-infesting insects.

Fumigants. To fumigate stored grain successfully it is necessary to create and maintain a uniform distribution of a poisonous gas throughout the mass of grain for a period long enough to kill the free living insects and their immature stages concealed within the kernels. This is most difficult on the farm since bins are usually loosely constructed and are often open at the top. Strong winds and high temperatures accelerate evaporation and loss of fumigant.

For best results in treating farm bins, the surface of the grain should be level and at least 6 in. below the top of the bin. If possible, the fumigant should be applied from outside the bin by means of a bucket pump or other type of sprayer, and should be distributed uniformly over the surface. Applications should be made in the cool part of the day and when the wind is not blowing. Fumigants and dosages recommended for various grains are given in Table V.

Fumigants may be applied to elevator grain in a number of ways: (1) surface application, (2) grain stream application, and (3) spot application.

The first type of application is designed primarily to deal with surface infestations, although with the large bulk, heavier-than-air type

of fumigants, complete kills may be obtained throughout the bin of grain by this method. Where surface infestation is involved, the various bin openings such as ventilators, manhole covers, and loading chutes should be effectively sealed. Materials suitable for sealing are discussed in detail in the section on warehouse fumigation (page 270). Best results are secured with liquid fumigants if the required dosage is applied in an atomized condition. The object is to retain the fumigant at the top of the bin rather than to have it sink down through the mass of grain. Where application is made with a sprinkling can, much of the fumigant sinks below the infestation level and its value is lost. The use of chloropicrin alone, applied by means of a garden sprayer to the space above the grain in closed-topped bins at the rate of 1.5 to 2 lb. per 1,000 cu. ft. of space above the grain, has yielded excellent control of the Indian-meal moth.

Where the entire dosage for the bin is applied to the surface it is often possible to make the application from the bin floor by the use of suitable pumping equipment and nozzle extensions which permit even distribution of the fumigant from the bin openings. This is to be preferred to application by means of a sprinkling can because of safety considerations.

Grain stream application is the best method of applying fumigants to grain where the infestation is general or deep-seated. In this procedure, the grain is transferred from the bin in which it is located to the one in which the fumigation is to take place. The fumigant is applied to the grain on the belt just prior to entering the tripper or to the grain stream as it enters the bin. This method of application ensures a uniform distribution of fumigant throughout the bin as well as increased dosage at the bottom and top to offset any leakage. The rate of application in a given time is easily calculated on the basis of the rate of transfer to the new bin.

Spot application has been used to control local infestations in spots some distance below the surface in temporary storages and in grain piles. The infested area is first delimited by probing, and the required dosage is calculated. A series of injections spaced about 2 ft. apart is made around the edge of the infestation. The calculated dosage is then introduced on the basis of 2-ft. squares within the buffered area, usually at two levels. While the treatment frequently yields only a partial control, it does hold the insects in check until the grain can be moved and treated more adequately.

In the fumigation of grain, it has been shown that a certain bulk of fumigant is necessary in order to secure satisfactory results. In general, at least 1.5 gal. of fumigant per 1,000 bu. of grain is required to

secure adequate distribution through the grain mass. Small bulk fumigants such as chloropicrin require the use of a carrier such as carbon tetrachloride to ensure adequate distribution.

In Table V some of the recommended dosages for the common grain fumigants under conditions of tight storage are given. The figures are for relatively clean, sound, dry grain. When large amounts of dockage are present or when the grain is of high moisture content, a considerable increase in the dosage will be required for successful fumigation. Dosages should be doubled for grain stored in wooden bins.

TABLE V

FUMIGANTS AND DOSAGES FOR THE TREATMENT OF GRAIN STORED IN STEEL BINS WHEN GRAIN TEMPERATURES ARE 80°F. OR ABOVE[a]

Fumigant	Mixture by Volume	Dosage in gal. per 1,000 bu.		
		Wheat, Oats, and Rye	Corn	Sorghum
Carbon tetrachloride *alone*	—	3	6	8
Carbon tetrachloride *with*				
Ethylene dibromide	19–1	2		6
Carbon disulfide	4–1	2	5	6
Ethylene dichloride	1–3	4	6	8
Ethylene dichloride (1:3) plus methyl bromide 10%		2	2	—
Chloropicrin	6–1	1.5	1	—
β-Methylallyl chloride	3–1	2	2	—
1, 1-dichloro-1-nitroethane	5–1	1.5	1.5	—

[a] At temperatures much below 80°F. dosages should be increased by 50%.

For the fumigation of wheat or barley in elevator storage, any of the fumigants listed in Table V can be used at the dosage recommended for treating wheat in steel bins. In wooden crib bins, the dosage should be doubled. These fumigants are best applied in aliquot dosages every 1,500 bu. as the bins are filled, although they can be applied uniformly over the surface of the grain if it cannot be moved. In addition to these fumigants, calcium cyanide at 10 lb. or chloropicrin at 2 lb. per 1,000 bu. can be used. They are applied with equipment specially designed to feed the chemicals into the grain stream at any desired speed and dosage. Oats require a slightly heavier dosage.

Rough rice in elevator storage may be fumigated successfully at the following dosages per 1,000 bu. in concrete elevators: carbon tetrachloride with carbon disulfide, 4–1 mixture, 2 gal.; carbon tetrachloride with ethylene dichloride, 1–3 mixture, 4 gal.; and carbon tetrachloride with

chloropicrin, 6–1 mixture, 1½ gal. In wooden crib bins the dosage should be doubled. For best results, these fumigants should be applied in proportionate dosages in the last 100 bu. of each 1,000 or 1,500 bu. draft as the bins are filled.

Milled rice in bin storage can be treated with surface applications of the fumigants and with dosages recommended for treating rough rice in concrete elevators. Rough rice may also be treated in concrete elevator bins with calcium cyanide at a dosage of 15 lb. per 1,000 bu. Bagged rough rice and milled rice in warehouse storage can be successfully fumigated with methyl bromide at 1¼ lb., or hydrocyanic acid at 1 to 1½ lb., per 1,000 cu. ft. of space. Other types of bagged grain in warehouse storage can be treated with methyl bromide at a dosage of 1 lb. per 1,000 cu. ft. of space.

Everyone who handles fumigants should realize that any fumigant that is effective against insects is also toxic to warm-blooded animals. This point cannot be too strongly emphasized. In applying fumigants to stored grain the fumigator should avoid inhaling any of the vapors, even those from light concentrations, and should also avoid spilling the liquid fumigants on his clothing or shoes. Many fumigants will cause blistering if they are held in contact with the skin in liquid or vapor form by means of soaked clothing, gloves, and shoes.

A gas mask provided with a full face piece and a canister adapted to protect against the particular fumigant being used should always be worn by anyone who is exposed to the vapors of fumigants during the treatment of stored grain. Only equipment that has been approved by the United States Bureau of Mines or by similar agencies in other countries should be used. More detailed information regarding the use of fumigants and protection devices may be found in United States Department of Agriculture Circular 720 (18).

Dust Treatments. When finely divided, chemically inert dusts are mixed with grain they promote the rapid loss of body moisture and cause the death of stored-grain insects by desiccation. Many such dusts have been recommended for use in treating stored grain. Ordinarily it is not deemed desirable to mix dusts with grain intended for human food, owing to the difficulty of separating the dust from the grain. However, in countries where modern storage facilities are unavailable, small quantities of grain stored in pits, baskets, or in containers raised on poles above the ground can be protected by treatment with one of the nonpoisonous dusts. Dusts suitable for this purpose are finely divided silica gel, rock phosphates, precipitated chalk, magnesium oxide, aluminum oxide, or other local material found to be satisfactory.

The dust should be thoroughly mixed with the grain until it is evenly

distributed throughout the whole mass. Dusts with a particle size of 1μ or less can be used at the rate of 1 part per 1,000 parts of grain by weight. Operators applying the dust should be protected by adequate respirators. Silica aerogel, at the rate of 1 part per 2,000 parts by weight, can be used as a surface treatment in farm bins to prevent invasion of grain by migrating insects. The effectiveness of inert dusts is progressively less, however, as the moisture content of the treated grain increases above 12%.

As preventive treatments for the protection of farm-stored grain from insect attack, pyrethrins in combination with piperonyl butoxide, sulfoxide, or other synergists in an organic or inorganic dust base are becoming more and more popular. For effective protection, grain must be dry and free from insect infestation at time of treatment. An inorganic diluent dust can be used for feed grains, but for wheat it is necessary to use an organic dust such as ground wheat dust as a carrier for the insect toxicant. Dosages range from 75 to 100 lb. per 1,000 bu. of grain.

Prevention and Control of Infestation in Cereal Products

Milled cereal products should be insect-free when placed in storage; otherwise they are likely to deteriorate rapidly and spread infestation to commodities already in storage. Finely ground products can be freed of all stages of insect life by redressing through a sifter clothed with 10XX cloth and then treated with a centrifugal force machine known as the Entoleter. Coarser-milled products can be treated with the Entoleter or sterilized by heat. A continuous-process sterilization by heat that raises the temperature of the product to 140°F. or slightly higher and maintains it at that level for about 10 minutes will ensure the death of all stages of insects that may be present.

Cereal products are highly attractive to insects; hence it is essential to package them in containers that will afford the greatest protection from infestation during subsequent storage.

The majority of the insects that infest cereal products have comparatively weak mouth parts and are unable to cut through substantial wrappers. Many of them are able to thrust their ovipositors through the meshes of fabric bags and lay their eggs directly in the cereal product within the bag. The immature stages of many insects are also able to crawl through the meshes and through needle holes along the seams and at the top or bottom where the bags are sewed. In such cases the more closely woven fabrics offer the greatest resistance to penetration. Bags made of paper, paper laminated to cloth, or back-filled fabrics and cartons of fiberboard offer more resistance to insect penetration than ordinary cotton or jute bags. However, unless these containers are ade-

quately sealed, small flat beetles such as the saw-toothed grain beetle and the larvae of other beetles and moths may easily penetrate through minute openings where the seals are imperfect. Most methods of sealing bags and cartons used commercially today are inadequate. If bags are closed by sewing, the sewed ends must be protected by the use of a gummed strip that will cover all needle holes. For fiberboard cartons the application of a wet-wrap cover offers the finest protection. Experimental work with insect repellents for incorporation in the adhesives used to seal fiberboard cartons and paper bags may help solve the problem, but has not yet reached a satisfactory conclusion.

Impregnation of fabric and paper bags with pyrethrins or pyrethrins and synergists has been found to afford considerable protection against penetration by insects. In fabric bags this protection is more efficient when the weave is close enough to offer some mechanical resistance against penetration. More powerful insecticides such as DDT, benzene hexachloride, chlordane, etc., have also been found effective, but are not practical for use in insect-proofing bags intended for packaging foods, owing to the danger of contaminating the food. It seems likely that insect-repellent chemicals offer the best means of providing an insectproof container. Packages impregnated with repellent chemicals are particularly useful in resisting the invasion of certain insects that have wood-boring habits.

The cadelle is probably the most troublesome of the boring insects, since it feeds on a wide variety of stored commodities and is widely distributed. It is primarily a pest of grain and flour, and is commonly found in railway boxcars, ships, warehouses, farm granaries, and other places in which foodstuffs are stored or transported. The larva, or immature stage, has the habit of boring into woodwork to form a sheltered place in which to hibernate or to transform to the pupal or adult form, and is equipped with jaws powerful enough to cut through any type of package. It will cut through a multi-wall paper bag or a metal-foil-wrapped carton overnight.

Termites also burrow through cartons and other packages that are stored in warm, damp locations, or in warehouses with wooden floors that are infested. The larvae of many insects, when fully grown, have the urge to migrate in search of pupation quarters, and larvae of the hide beetle, *Dermestes vulpinus* (F.), and other insects have been known to leave the hides or other commodities in which they were breeding to burrow by the hundreds into packaged products of all kinds stored nearby.

Infestation in Transit. It is unlikely that more than a small proportion of cereal products will be packaged in insectproof containers for

many years to come. It is therefore essential to safeguard them in transit by providing transportation that is insect-free. Public carriers including railway cars, ships, and barges that transport grain and other susceptible foodstuffs invariably become infested with insects and harbor large insect populations in woodwork or in accumulations of grain and grain dust behind partitions, in cracks, etc. In railway cars this condition is much worse during warm seasons of the year.

Railway cars can be cleaned to a certain extent by air blowing; however, this will not remove infestations in woodwork and infested accumulations from behind end linings. Spraying with pyrethrum, DDT, or other residual sprays has been found helpful. Application in the form of a coarse spray is superior to fogging methods. To protect cereal products from contact with sprayed surfaces, cars should always be lined with paper.

Ships and barges can best be freed of infestation by fumigation with hydrocyanic acid gas, 8 oz., or methyl bromide, 1 lb. per 1,000 cu. ft. of space. However, large fans are necessary to ventilate the holds prior to loading, and it is necessary for crew members to vacate the ship during fumigation and aeration. When it is necessary to save time, spraying is recommended as a substitute. A pyrethrum-oil spray containing 0.8% pyrethrins has proved to be highly effective for this purpose.

Inspection Before Storage. Regardless of the method of transportation used, all shipments of milled cereal products intended for storage should be carefully inspected before they are unloaded and placed in storage. Inspection of the bags may indicate the presence of infestation by the finding of insects crawling over them. In all cases a few bags taken at random should be sifted to determine the true condition of the product. A No. 64 wire sieve will be found useful for this purpose.

Cereal products that arrive at destination with insects crawling over the bags but not otherwise visibly infested should be fumigated before they are placed in storage. This can be done in railway cars with methyl bromide at the rate of 6–10 lb. per car. Products arriving by other forms of transportation can probably be best fumigated in atmospheric vaults with methyl bromide at 1 to 1½ lb. per 1,000 cu. ft. of space.

In the United States milled cereal products, intended for human food, appreciably infested with insects are considered unfit for use as food and must be diverted to feed. In countries without such regulations it is permissible to recondition infested flour by sifting or by returning it to the mill for reconditioning.

Infested feeds should be fumigated with methyl bromide at the same dosages recommended for flour.

Warehouse Construction. Warehouse storage should provide adequate

protection from the weather and from the attack of rodents and insects. If possible, warehouses should be of modern, tight, concrete, or brick construction, easy to keep clean, and suitable for fumigation. It is unlikely that this kind of storage will ever be universal and at the present time only a very small percentage of warehouses are of this type.

Much can be done to improve the condition of old, poorly constructed warehouses. Every effort should be made to eliminate dead spaces in walls and floors where accumulations of grain products offer harborage and food to insects. Double, hollow walls and partitions should be eliminated. If floors are of wood, all cracks should be filled or kept clean of dust or accumulations of cereal products. All caked material should be scraped off. Mop boards should be removed and openings where floor and walls meet should be filled with an elastic cement, such as a good calking material or a good grade of roofing cement. All cracks around posts should be similarly filled. Cracks in walls should be filled and the walls painted.

Old wooden floors or even badly worn concrete floors are difficult to clean and keep clean. They can be renovated by laying quick-setting plastic preparations over the old ones. Adequate light and ventilation should be provided. Most insect pests of cereal products shun the light and seek dark corners in which to hide.

Flour-handling equipment, bag-cleaning equipment, and all other machinery likely to harbor insects and difficult to keep clean should be removed from storage warehouses. Flour bins, if present, should be constructed so that workmen can clean around them. Wooden bins should be supplied with enough clean-out doors so that the entire unit can be cleaned. If possible, loading docks should be constructed so that waste grain or milled products cannot accumulate under them. Insects breeding in such accumulations are a constant source of infestation in seasons of warm weather.

Warehouse Management. Efficient warehouse management can do much to prevent losses from insect infestation. Flours should be stored in rooms separate from feeds and other foodstuffs to prevent cross infestation. If possible, patent flours should be separated from whole wheat and rye flours for the same reason. Flour should be stacked on racks in piles at least 12 in. from the walls of the warehouse and far enough apart to allow inspection and cleaning. Racks should be inspected regularly for infestation, cleaned by blowing with compressed air or a portable blower, and the undersides sprayed with a residual spray. The tops may be sprayed with a pyrethrum spray. Where racks are not available, the flour can be stacked on paper. Lift platforms are sometimes used and are excellent.

Stocks of flour or feed longest in storage should be moved first. It is a good idea to tag each shipment so as to remove all doubt as to the length of storage. Pile each shipment separately and in an orderly manner. Do not pile a new shipment on top of an old lot or near any odorous material. Keep stacks of flour clean and free of dust. Whenever a stack is disposed of, the space formerly occupied by it should be swept, vacuumed, and sprayed. Strict sanitation in the warehouse cannot be emphasized too strongly. No accumulation of dust, flour, feed, or other product in which insects can breed should be allowed in the warehouse. Bags of flour or feed that are broken should be disposed of at once and not allowed to accumulate or stay in the piles.

Walls and floors should be sprayed periodically with a residual type spray as a preventive measure. This will aid materially in preventing trouble from migrating insects. If the warehouse is filled or partially filled, the piles of bagged material must be covered during spraying operations to prevent contamination.

Perhaps the best insurance against trouble is regular inspection of warehoused products. During periods when the temperature of the product is 70°F. or above, an inspection should be made every 30 days and in any case at least every 90 days. The inspector should look particularly for moths resting on the walls or bags during the day or flying at dusk, the presence of webbing on the bags, beetles or worms underneath or between bags, small piles of flour or feed on bags, insect tracks on floor, or holes cut in paper bags.

Lots found to be infested should be disposed of immediately to prevent the spread of infestation to uninfested lots. A fumigating vault capable of holding a carload of material will be found most useful for treating such products. If necessary, the entire warehouse may be fumigated to destroy incipient infestations. As a matter of policy, no returned goods or used bags should be allowed in the warehouse. They should be disposed of without bringing them near the storage building.

Sprays. For the control of insect infestation in the woodwork and dunnage of ships, railway cars, and storage warehouses of all kinds, for general clean-up purposes in warehouses, and for the control of certain types of flying insects, sprays are quite useful.

Against flying insects and for general clean-up work where a comparatively nontoxic material is desired, a pyrethrum-oil spray can be employed. Extract of pyrethrum (total pyrethrins not less than 0.8%) in a high-grade oil carrier can be atomized for use against flying moths or applied in a coarser spray with an electric blower-type sprayer or a knapsack sprayer. Such sprays when atomized or applied as a fog do not leave a very substantial insecticidal film and are of limited value in the

control of warehouse infestations.

Residual sprays of DDT, TDE, methoxychlor, benzene hexachloride, and toxaphene, while toxic to warm-blooded animals, leave insecticidal films that remain effective against insects for considerable periods. They are useful for treating walls, floors, and partitions of storage places to combat infestations in woodwork, to kill insects crawling over sprayed surfaces to reach stored foodstuffs, or flying insects that come to rest on sprayed surfaces.

These sprays are available in oil or emulsion concentrates or as wettable powders. In general, an oil base will be found most practical to use, although each formulation has certain advantages. A 5% concentration of any of these materials will be found effective when applied at the rate of 1 gal. per 1,000 sq. ft. Residual deposits of DDT have been found to remain effective longer than other materials. In regions with a cool climate two applications yearly in April and in July should afford adequate protection. In warmer regions a regular schedule of treatments every 3 months may be necessary. Warehouses should be as nearly empty as possible during spraying operations. Any materials in the warehouse at time of spraying should be covered to protect them from the spray. Residual sprays should be applied in a coarse spray with an electric blower-type sprayer or a knapsack sprayer. Bagged foodstuffs should never be allowed to come in contact with sprayed surfaces.

When dissolved in oil, residual insecticidal spray materials are readily absorbed through the skin, so that in handling or applying them in this form, care should be taken to avoid contact with the skin. It is also advisable for the operator to wear a suitable respirator while applying them.

Fumigants. The fastest and most effective method of destroying insect infestation in milled cereals and in warehouses in which they are stored is by fumigation. Owing to the fact that it is only absorbed to a small extent, and penetrates stacks of milled cereals with ease, methyl bromide is the ideal fumigant for well-filled warehouses. However, it is only effective in buildings that have been made thoroughly airtight. Hydrocyanic acid gas can be used in buildings that are reasonably tight, but is useful chiefly for freeing empty warehouse space from insect infestation. It does not penetrate well into bags of milled cereals.

Many warehouses are so poorly constructed that they cannot be fumigated successfully, in which case it is necessary to fumigate milled cereals under tarpaulins or in vacuum or atmospheric fumigation chambers. Railway boxcars can be used if necessary, although they are not usually of very tight construction and need a lot of sealing. With any warehouse it is important to prepare adequately before releasing the fumigant. All

windows, doors, skylights, and other openings should be tightly wedged or sealed and any broken panes replaced so that fumigants will be retained as long as possible. Loosely fitting window sashes should be sealed with paste and paper or "puttied up" with flour and oil mixed to the consistency of putty. Calking cement applied with a calking gun is also useful for pointing up around window frames, door frames, and pipes and for filling cracks. Another mixture suitable for this purpose consists of four parts of asbestos fiber, one and one-half parts of calcium chloride, and two parts of water. Large sliding doors that fit imperfectly can be calked with the flour-and-oil paste or the asbestos-calcium chloride mixture.

For stripping window frames that are only slightly loose, gummed paper, adhesive tape, or strips of newspaper or kraft paper may be used. Some of the adhesives that can be used with the paper are ordinary flour-water paste, paper-hangers' paste, casein-base paste, sodium silicate, tin paste, synthetic rosins, and cup grease. Although cup grease will stick to practically anything, it is generally used only as a last resort on surfaces to which nothing else will adhere. It has the disadvantage of adding to the fire hazard, and the sun's rays will melt it. It neither dries nor sets; therefore, seals made with it will not stand much wind pressure.

When it is impossible to tighten a window or other aperture by the ordinary method of sealing or stripping, it is necessary to seal the entire aperture. For this purpose a fiber-reinforced waterproof paper or car-lining paper can be used. When methyl bromide is used as the fumigant, the paper employed for sealing purposes should be smeared with oil or grease to make it gastight.

Warehouse fumigations should be made when there is little wind since there is considerable air leakage with many seemingly tight structures. Temperatures should preferably be above 70°F. If hydrocyanic acid is used as a space fumigant for empty warehouses, a dosage of 8 oz. per 1,000 cu. ft. of space is adequate. When methyl bromide is used, a dosage of 1 to 1½ lb. per 1,000 cu. ft. of space is adequate if the temperature is above 60°F. For temperatures below 60°F. an additional ½ lb. per 1,000 cu. ft. should be added for each 5-degree drop in temperature. To obtain uniform distribution of the fumigant and to prevent stratification of the vapors of methyl bromide, electric fans should be operated for 1 hour after the release of the gas.

Owing to the fact that fumigants are lethal to warm-blooded animals as well as to insects, warehouse fumigations should be conducted by professional fumigators who understand the risks involved and take the necessary precautions to safeguard themselves and others.

In the fumigation of bagged cereals under tarpaulins, a rubberized

or plastic-coated tarpaulin is thrown over the stack and the edges weighted down to prevent gas leakage. Provision is made for an air dome at the top of the stack by using two sacks placed edgewise about 4 ft. apart. This air dome will provide free air space to permit diffusion of the gas. Methyl bromide is recommended for this type of fumigation. It is readily applied by use of plastic tubing leading from the outside to the air dome on top of the stack. The outside end of the plastic tube can be connected to a cylinder of the methyl bromide by standard connections and the required dosage weighed in. One-pound cans can also be used if desirable. A special opener which can be connected to the tubing punctures the can by a simple device and directs the fumigant through the plastic tubing under its own pressure. After one can is emptied it can be replaced by others until the proper amount of fumigant has been applied.

For use in treating milled cereal products in atmospheric vaults, methyl bromide is recommended at a dosage of 3 lb. per 1,000 cu. ft. of space for an exposure period of 24 hours. In vacuum chambers methyl bromide can be used at the rate of 4 lb. per 1,000 cu. ft. of space for a 3-hour exposure period or at 3 lb. per 1,000 cu. ft. of space for a 15-hour exposure period. An initial absolute pressure of 2 in. should be obtained, and the fumigant should be recirculated for 15 minutes after introduction.

Railway boxcars loaded with milled cereal products can be fumigated with methyl bromide at a dosage of 10 lb. per car for an exposure period of from 12 to 18 hours. With exceptionally tight cars this dosage can be reduced to 6 lb. Before applying the gas the doors should be sealed with masking tape or some of the sealing materials suggested for sealing warehouses. The methyl bromide should be applied from the outside of the car through plastic tubing that has been inserted through a hole drilled in the floor of the car to a point above the center of the car. After the gas has been applied the tube can be withdrawn and the entry hole plugged.

Precautions to be taken in the handling of fumigants are given in the section on fumigants for stored grain (page 263). More detailed information regarding the fumigation of milled cereal products and protection devices may be found in United States Department of Agriculture Circular 720 (18).

Fumigated railway cars and fumigating vaults or rooms should be thoroughly aerated before unloading operations are commenced in order to avoid danger to workmen.

Prevention Is Better than Cure

Too much cannot be said regarding the need for preventing damage

to our stored cereal products. World populations are increasing at a tremendous rate whereas our tillable soils are being reduced or impoverished by soil erosion and improper management. Most of the people of the world are on a substandard, carbohydrate diet and go to bed hungry. There is no such thing as a surplus of cereal foods. We cannot afford to let insects destroy a single bushel.

The grain grower who waits until his grain bins are crawling with weevils and the warehouseman who does nothing until the moths are flying in clouds in his storage rooms are somewhat like the farmer who waits until insects have eaten all the leaves from his fruit trees and the fruits are all wormy and then asks what he can do. Obviously, the damage has been done. If we are to prevent losses from insects, measures must be adopted to make it difficult or impossible for them to obtain a foothold in our granaries and storehouses, and frequent and regular inspections must be made to eradicate infestations as soon as they are discovered. Eternal vigilance is imperative.

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Rodents

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Unfortunately, the storage of cereal grains and their products is not confined to modern elevators and rodentproof warehouses where protection against loss and contamination by rats and mice would be a relatively simple matter. Even in recent years, in both the United States and Canada, some threshed wheat from bumper crops has been piled on the ground with little or no protection from rodents, birds, insects, and weather. From this extreme, grains of all types are stored on farms, and in small communal centers throughout the world, where the greater portion is without benefit of even partially rodentproof structures. Aside from the miscellany of sheds and bins of all types, we find grain held in ricks (field stacks of unthreshed grain) for varying periods of 3 to 9 months in England and parts of eastern Europe (47), in underground pits in France (58), in sand ditches covered by sand and in "shounas," which are little more than fenced yards under the open sky, in Egypt (3), in open-ended bamboo mat cylinders in China (36), and in many other ways. It is true that the grower absorbs a great deal of the loss inflicted by rodents on farm-stored grain; nevertheless, the impaired quality and the increased cost of the fraction that reaches the market are passed on to the cereal processor and thence to the public.

Of greater concern than the quantity consumed or lost is the contamination of the remainder with rodent urine, excreta, hair, and extraneous debris. Southern (47) remarked after watching the threshing of grain held in field ricks, "It is an impressive sight to watch a sack (intended for chaff and dust from the thresher) filling up almost entirely with mouse droppings." An undue proportion of the expense of flour milling must be devoted to screening, washing, scouring, aspirating, and otherwise cleaning grain before it enters the break rolls. Unfortunately, grain cleaning machinery in use today, with probably rare exceptions, was not designed specifically to remove rodent filth (25). Mouse pellets being approximately the size of a grain of wheat are very troublesome. There is no efficient dry-cleaning process for removing rat pellets from

corn. Furthermore, rodent hair, whether air-borne or from excreta, often becomes so thoroughly enmeshed in the plant hairs at the tip of a kernel of wheat that washing does not successfully dislodge it, and little, short of severe scouring that removes the wheat hairs, will lower the rodent hair count in the finished product (25). Protection of stored grain must therefore apply to field shock or stack, threshed farm storage, local elevator, terminal elevator, and processor's premises, as well as in transit by cart, truck, railroad car, or ship—a stupendous undertaking.

The protection of cereal products against rodent loss and contamination is neither so complicated nor difficult because better housing conditions are ordinarily available for these finished products. Nevertheless, rodent contamination, torn sacks, and broken retail packages result in staggering waste from the standpoint of human consumption. Indifference or negligence sometimes contributes to the rodent losses in the modern mill and warehouse, as reasonably effective means of rat and mouse control are available.

Although this discussion is limited to the problems of grain storage, we can hardly disregard the general rodent problem of the farm (35) and community (37), or the town and city, in which the cereal is held. The cost of maintaining rodent-free storage will be in direct ratio to the degree of reinvasion of the premises from the surrounding rodent population reservoir, against which no rodentproofing is entirely adequate.

Commensal Rodents

The term "commensal" means "one who eats at the same table." Members of the Old World family of rodents *(Muridae)* are certainly our uninvited guests. It would be impractical here to identify the hundreds of forms of rats and mice that constitute this group (27). More than 50 subspecies of roof rats (*Rattus rattus* Linnaeus) have been described in the Central and Southern Pacific area alone. For practical control considerations the commensal rodents can be grouped into three types, burrowing rats, climbing rats, and mice.

Burrowing Rats

The Norway rat (*Rattus norvegicus* Erxleben), originating in the Old World, has extended its range via commercial routes to many points of the globe. It is now found throughout the United States and well into Canada; in point of numbers and distribution it is the predominant rat species. This blunt-headed, heavy-bodied brown rat has pronounced burrowing habits. Adults average about ¾ lb. (340 g.) in weight, 16 in. (40 cm.) in length, and the scaly, blunt, nearly naked tail is slightly shorter than the head and body. It easily adapts itself to all manner of human installations—residences, buildings, livestock and poultry sheds,

sewers, garbage dumps—and in the more temperate zones or seasons it also has its burrows in the fields and along banks of streams and ditches. It nests in shallow burrows (43) or beneath low platforms and floors, in double walls, in long-unmoved stores such as machinery, merchandise, and foodstuffs—but principally at ground floor levels. In feeding it is omnivorous, accepting meats, fish, cereals, fruits, and vegetables.

Of particular import is the fecundity of this family of rodents. The Norway rat, for example, will have litters averaging eight young (18, 20, 22, 41), and since the period of gestation is but 21 days there is a possibility of some 12 repetitions in a single year, although in most circumstances only four to six litters a year result. The young are mature in about 4 months and add to the mounting total with litters of their own. Emlen (28), from studies of 23 free-living populations of Norway rats in Baltimore, Maryland, states that populations reduced between 50 and 90% by control methods recovered at a rather constant rate of 4% of their original level each month.

Climbing Rats

The roof rat is typically a climbing rat, and in general is smaller, more slender, and longer tailed than the Norway or burrowing group. In color its subspecies vary from gray through brown to blue-black, all having lighter underparts. The adult Alexandrine rat (*Rattus r. alexandrinus* Geoffroy) is gray, the face is slender and pointed, and the ears large. On the average this rat weighs ½ lb. (225 g.) and is 15 in. (38 cm.) in total length with the relatively slim, tapering, and naked tail exceeding the length of the head and body. Two other subspecies exist in the United States: *Rattus r. frugivorus* (Rafinesque), which so closely resembles the Alexandrine that it is of interest principally to a taxonomist, and *Rattus r. rattus,* which is easily distinguished by its blue-black color. According to H. J. Spencer (51) the northern limit in the United States of the species *rattus* in numbers sufficient to constitute a community control problem is a line running from El Paso, Texas, through Dallas, Shreveport, Birmingham, Atlanta, Augusta, to Charleston, South Carolina. Within this limit it constitutes fully 50% of the total rat population. H. J. Spencer points out that the populations of Norway and roof rats have no fixed ratio. In Florida, for example, Norway and roof rats are found in about equal numbers in the seacoast towns of Tampa, Miami, and Jacksonville, whereas inland the roof rat predominates in the proportion of 2–3 to 1. A number of towns like Gainesville, Florida, have roof rat infestations exclusively. Along the west coast of the United States roof rats again appear in numbers and, according to Storer (52), are found in much of lowland California.

Roof rats are nimble climbers and can negotiate the rough outer

walls of a building, small diameter perpendicular pipes or pipes of any diameter that are within an inch of a wall, electric wires and telephone cables, vines, and trees. By such means they gain access to buildings at innumerable places (unscreened windows, roof ventilators, unused chimneys, vent pipes, etc.) and, if not crowded to the upper floors by an accompanying infestation of Norway rats, will nest throughout the building. The litters average about seven young (17), but in gestation period and other breeding particulars they closely parallel the Norway rat. While accepting a wide variety of food, roof rats tend to be vegetarians, preferring fruits, vegetables, and cereals in that order.

Mice

House mice (*Mus musculus* Linnaeus) represent the third group of commensal rodents, two subspecies of which occur in the United States (31). These are very small rodents; adults weigh but ½ to ¾ oz. (15–25 g.) and measure 6–8 in. in total length with the tail about equaling the head and body. They are brown in color with pale underparts, and the tail is sparsely haired. One of the best distinguishing characteristics is the strong musky odor house mice possess, an odor that soon pervades the room and the stocks it contains.

Because of their small size, secretive nature, and ability to live without water for considerable periods (51), the distribution of house mice throughout the world has been speeded by transport in bales of goods and packages of foodstuffs. Since they climb readily they infest a building at all levels. Their nests are hollow balls of shredded paper, cloth, or fibrous waste located in dark recesses of the building and in food stocks that are moved infrequently. Laurie (34) shows that the litter size as well as the number of litters produced by a single female during the year varies with the habitat and food available. The average litter size reported by him is 5.6 young. House mice living on white flour in storage depots in England had an average of 7.97 litters per year for a total of 44.63 embryos per female. These mice are known to increase rapidly under favorable circumstances, reaching densities of several thousand per acre. They are principally seed-eaters, which accounts for their importance in the handling and storage of cereal grains.

Many species of small rodents cause damage to stored cereal grains at the farm level. In North America these include deer mice *(Peromyscus)*, meadow mice *(Microtus)*, wood rats *(Neotoma)*, various ground squirrels (including *Citellus, Eutamias,* and *Tamias)*, and tree squirrels *(Sciuridae,* in part). Their control is so varied as to require treatment elsewhere than in the present volume. As previously stated, much of the grain held on farms is in very loosely constructed buildings or shelters. It is not unusual for domestic poultry and pigeons, as well as sparrows

and other seed-eating small birds, to have access to this grain. While that eaten by poultry cannot be said to constitute a waste of grain, certainly the sanitary condition of the grain over which these birds have fed creates a milling problem. In a similar fashion, the domestic cat, so often used to cope with the rodent problem, is no less objectionable as it hunts rodents and beds in this same grain.

Economic Losses Caused by Rodents

Chitty (8) and Thompson (55) have shown that Norway rats of an all-age group in their natural habitat would accept an average of 24 g. of wheat per day per rat in addition to other foods they might procure; this means 20 lb. of grain per year actually consumed as an average by each rat. To the cost of feeding the rats, we must add the waste from rodent contamination and the considerable expense of maintaining food sanitation. The rodent makes its presence a burden in still other ways. There is considerable damage to buildings and milling machinery from rodent gnawing. Shadle (45) demonstrated that each of the four incisor teeth of the rat grew approximately 5 in. in length each year. Feeding on hard foods, cutting through obstructions, and burrowing serve to keep these teeth worn off. We must also contend with gnawing to gain entrance to food stores, and the idle and inquisitive gnawing on conveyor belts, plastic and composition machinery parts, plumbing, and on insulation of electric cables.

But the total cost has not been levied for the support of the commensal rodent population until it includes the loss of man-hours of work through sickness and death as a result of rodent-borne diseases. Bubonic plague has long stalked the world with the rat its principal vector. Murine typhus is an endemic form in the Western Hemisphere, and its prevalence appears to have increased markedly in the southern part of the United States in recent years. It is of particular interest here, for "the disease occurs most commonly among workers in food handling establishments" (26). Davis (18, 24), reporting on the analysis of typhus antibodies found in rats trapped in San Antonio, Texas, states: ". . . grain mills had a significantly higher per cent positive than did stores or residences." Leptospirosis (Weil's disease), trichinosis, rat-bite fever, rickettsial pox, and bacterial food poisoning are other rodent-borne diseases that exact their toll.

Rodent Behavior as a Basis for Control

The success of any program to secure and maintain rodent-free premises will depend largely on the operator's knowledge of the habits of rats and mice. The intelligent application of such tools as traps, poison baits, and poison gas is of more import than the tools themselves.

Habits by Species

Of first importance is a knowledge of the kinds of rodents on given premises. Information as to *size* will give an index of the mesh that must be employed in rodentproof screens, familiarity with the *climbing or burrowing habits* will indicate the thoroughness with which the building will have to be made rodentproof, and data on *food habits* will point to the baits that will be most acceptable in control operations. Consideration of the feeding range of an individual species is of primary importance in the placement of baits and traps. A colony of house mice may exist in the cluttered corner of a room or in the interior of a pile of sacked grain or flour without leaving a sign of activity a yard beyond. Southern and Laurie (47) report that house mice living under "domestic" conditions occupy an area averaging only 50 sq. ft. In stacks of unthreshed grain they found mice occupying a similar area within the stack, but with little vertical movement within the stack. When poisoned baits were placed shoulder high completely about the perimeter of the stack, dead mice were confined largely to this level when the stack was examined at threshing. The Norway rat has a much wider range but again is no great traveler. Davis, Emlen, and Stokes (21) live-trapped, marked, and released 1,112 Norway rats in the city of Baltimore and on an adjacent farm (19). Of the marked rats recovered, approximately 80% were recaptured within 40 ft. of the original sites. Their movements, however, depend a great deal on the character of their habitat so that long trails may connect suitable harborage with a source of food supply. Petri and Todd (42), in studying the home range of *Rattus rattus* in Egypt, reported a restricted range, but H. J. Spencer (51) suggests that roof rats in southeastern United States may range throughout a city block if harborage and food are thus separated.

The reluctance of commensal rodents to cross open spaces is another trait that limits and modifies their feeding range. Calhoun (7) demonstrated that even in artificially supersaturated populations, Norway rats seldom left the city block in which they were released. Investigations in rodent ecology, at the Johns Hopkins School of Hygiene and Public Health, Baltimore, Maryland, indicate that city streets are reasonably effective barriers to movements of the Norway rat. Even an 8-ft. alley serves as a check to rat movements, for in a single night less than 10% of the rats living in a block crossed this space (21). The roof rats, making use of electric overhead cables and similar travel lanes, are not so limited by open spaces (51). Thus, reinfestation of an elevator or mill located in a city is most likely to result from rats harboring in the immediate vicinity, the company yards, or from neighboring premises, and attention should be directed toward maintaining this buffer area.

The harvest season, with the removal into storage of crops that had served for cover and food, followed by freezing temperatures that further reduce the cover and food, forces commensal rats and mice to make a concerted move indoors. The next few months often constitute a period of increased breeding activity. Timing of control programs to prevent the establishment of excessive resident populations is thus indicated.

Secretive and Wary Nature of Rats and Mice

Although rats and mice may be seen feeding at almost any hour of the day, the high point of their activity is at night, with emphasis on the first few hours after dusk. In addition to using darkness as a cover, both rats and mice avoid open spaces and have their runways along walls and behind and under obstacles; they also keep as close to some point of refuge as possible. Food occupying an exposed position is removed piecemeal to a protected site before being eaten by the rat. Experimenting in England, Thompson (55) observed that an occasional rat would sit beside the exposed food for a few minutes, but the majority would run to the bait pile, seize a mouthful, and dash away again. Individual marked rats made from 30 to 70 visits in less than one hour. Norway rats often have several well-established feeding retreats, termed "shucking stations" by Pisano and Storer (43), to which they bring most food to crack, hull, and eat. These secluded dining rooms are equally typical of rodent burrows or runways within a building. Even within their accustomed haunts any disturbance such as an unusual sound, change of lighting, or presence nearby of man or animals will cause temporary cessation of rodent activity. Note in the studies by Thompson (Fig. 3) how the passing of a train, or the wind rattling the sheet-iron roof of the shed, caused the rats to stop their feeding visits to a pile of grain. In restatement: poisoned baits should be distributed just prior to the period of highest daily activity of the rodents, should be in the natural runways which the rodents are loath to leave, should be wherever possible under cover or closely adjacent to some refuge where the rodents feel free to feed, and, lastly, should be planned so that there will be as little disturbance as possible after the baits are distributed.

Sensitivity to Change

Within a grain elevator or mill where little change is made from day to day in the structure, arrangement of machinery and stores, and the conduct of operations, Norway rats tend to form regular habits of travel, of feeding, and of food selected, in marked contrast to rats occupying a city waste dump. Habit combined with natural wariness causes a temporary avoidance of anything new whether it be a trap, permanent bait station, or harmless obstacle placed in the rats' regular runway. Experiments by the Bureau of Animal Populations, Oxford, England (4),

have shown that boxes placed along a regularly used runway caused rats to avoid that path for the next 3 days. Even moving a familiar object a short distance may evoke caution, and rats have occasionally been observed circling a place from which an object was removed in preference to taking the short route open to them. A strange object, like a bottle or piece of metal, placed near a pile of grain where the rats were accustomed to eat, appreciably retarded food acceptance there (9, 48).

The reaction to a new food is equally impressive. Chitty (9) made a detailed study of the reaction of wild Norway rats to a known amount of wheat placed about buildings and stock pens in England. The amount consumed each night over a 7-day period increased regularly (Fig. 1). Wet bread was then substituted for the wheat but without changing the feeding site. The consumption immediately dropped off, and it required 3 days before the quantity returned to the wheat level. A third change was made back to wheat, and although the drop in acceptance was not marked, still the same behavior pattern persisted despite the conditioning to change.

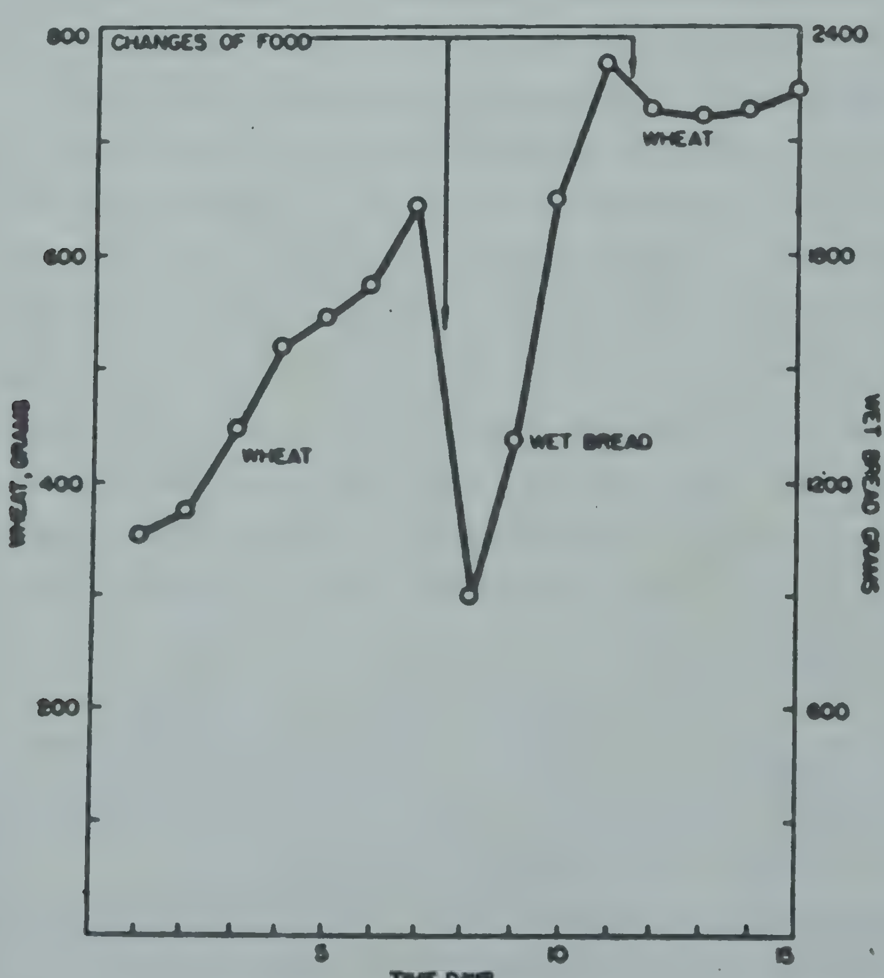

Fig. 1. Comparison of the dry weight of cereal food eaten by a colony of Norway rats on successive days. Illustrates the wary reaction of rats to a change of food. Reproduced from studies by Chitty (8, 9).

Crabb and Emik (10), working with a small Polynesian rat *(Rattus exulans)* and a member of the roof rat group *(Rattus r. neglectus-diardii)*

in the densely wooded interior of the island of Guam, demonstrated, under very different settings, exactly the same sensitivity of rats to change. Greatest discrimination was exhibited during the first 2 days of the bait-acceptance trials. Then in succession came, first, a cautious reaction to new food followed by an increase in acceptance over a 4-day period; second, temporarily greater acceptance of an accustomed food than of an otherwise more palatable *new* food when offered simultaneously; and, finally, a reduction in consumption of familiar foods when rotated in the accustomed feeding site.

A third variation of the sensitivity to change could be illustrated by altering the placement of a familiar item of food to a new site along the rat runway system. The rat, as well as many other wild animals, at first avoids or ignores the new feeding site, preferring its accustomed place. (See section on "Bait Handling and Placement" for application of information on rodent wariness.)

Control Measures

Rats and mice require three conditions to maintain their populations in connection with storage of grain: secluded shelter, adequate food, and a minimum of competition. Rat-free premises can be attained by attacking the problem from any one of the three approaches, but a combination is usually more practical.

From a long-range viewpoint, the construction of rodentproof storages and buildings is the most inexpensive type of rodent control. In fact, rodentproofing is a very necessary feature of any new grain-storage structure designed to deliver products to producers and/or consumers with a minimum loss in quantity and quality. Obviously, rodentproofing is an essential part of the general sanitation program. So costly is the process of cleaning grains that have become contaminated with filth (hair, urine, and feces of domestic pets, rodents, and birds), and so exacting are government regulations with respect to the marketing of contaminated consumer products, that the milling industry is seriously concerned with the position in which it is placed. The time is not far off when penalties will have to be imposed on unsanitary grades of grain.

Low-cost construction with local building materials, such as is characteristic of many farm grain storages, need not sacrifice rodentproofing. In the corncrib illustrated in Figure 11, Chapter VII, little or no attention has been given to this important phase in design. The large wire mesh permits free access of rats and mice, while sparrows, pigeons, and other birds gain entrance under the eaves. This corncrib, together with some other types of farm storage for grains, has so little clearance off the ground that an excellent burrowing harborage for Norway rats is created.

At very little addition in construction costs these defects can be avoided. For details on ways of rodentproofing new grain storages, the reader is referred to bulletins published by Silver, Crouch, and Betts (46), and by the United States Public Health Service (57).

Good Housekeeping

It is essential that good housekeeping be practiced within a building to limit places where rodents can nest, and as far as possible to keep food from their reach. New rodentproof structures must be carefully maintained. This phase receives too little attention, with the result that the substantial expenditures on original construction are often wasted. In a busy mill there is an almost continuous program of alteration, of machinery placement and repair, of plumbing, and of electric wiring, which often involves breaking the outside protective "armor." Loading doors and windows are often broken, screens and metal ventilators become rusted and weakened, storm and other weather damage occurs, all of which should receive prompt attention. In the larger commercial establishments it is suggested that a regular monthly itemized inspection be made by designated employees for the purpose of locating and repairing rodent and insect entries. Likewise, old structures benefit by inexpensive and partial rodentproofing. For farm corncribs to the large terminal elevator and warehouse, instructions are available governing patch-repair (46, 54, 57). Weights of sheet metal that will withstand rodent gnawing, gage and mesh size of wire screen that prevents rat or mouse entry, formulas for cement, directions for construction of "curtain walls," designs for constructing guards on pipes, electric wiring, flues, and ventilators, and plans for flanging doors and windows are all readily available. These simple measures will more than pay for the cost of their installation in preventing rodent damage and contamination.

Good housekeeping is equally essential whether the structure is rodentproof or not. Orderliness is a boon to storage operations and at the same time contributes materially to rodent infestation control. Dead storage areas that contain broken or old machinery and parts that "might sometime be useful" are excellent nesting refuges for rodents, as are jumbled accumulations of discontinued stock items, cartons, and other containers. All rooms within the building should be policed to reveal storage of any items that are rarely moved and thus form rodent harborage. The program should include the elimination or correction of sealed-off areas such as double walls, enclosed platforms and stairways, and other boxed-in shaftways and machinery to which rodents have access for nesting. Attics should be free of litter and easily accessible to regular inspection and control. Basements and substructure areas that have dirt floors in which rats burrow should either be sealed off by

concrete curtain walls or covered with concrete. By these means the building becomes less habitable for rodents that *require* seclusion.

Measures that seek to eliminate rodent harborage and reduce the sources of food and water supply are necessary adjuncts to control by means of poison and traps. Davis (20) in reporting the history of rodent control of two city blocks in Baltimore, Maryland, clearly shows the beneficial effect of sanitation in supporting control by poisoning of Norway rats (Fig. 2).

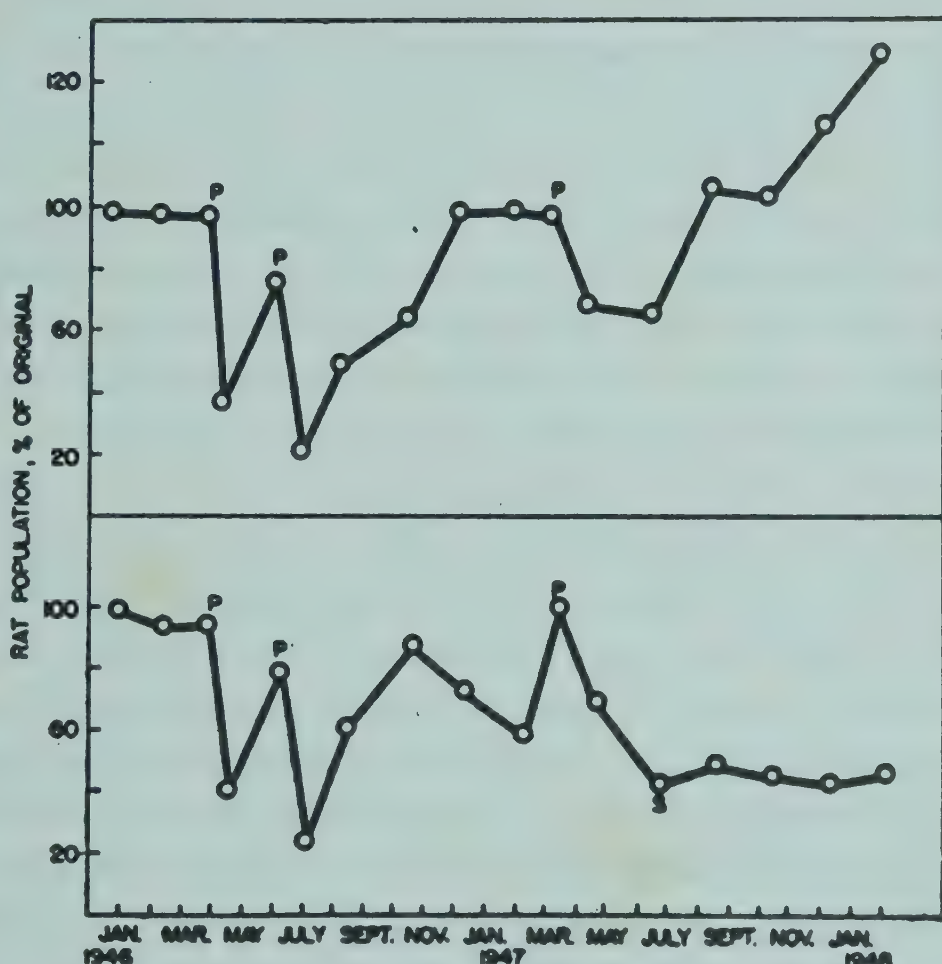

Fig. 2. Effect of poisoning (P) and sanitation (S) on the Norway rat population in two city blocks, Baltimore, Maryland. Illustrates the temporary nature of poison control unsupported by sanitation. Reproduced from studies at Johns Hopkins School of Hygiene and Public Health by David E. Davis (20).

In the course of plant and storage maintenance it is essential that a rodent infestation be recognized and checked before it becomes troublesome. Do not depend upon seeing live rats and mice, but judge their presence by the signs they leave. Rodent fecal pellets will accumulate along the walls, in dark corners, on shelves, and along ceiling joists. These excreta are dark and lustrous if recent and turn gray and dull with age; but if the natural travelways of rodents are regularly brushed and cleaned there should be no difficulty in detecting the presence of new invaders. Tracks in the dust are another easily read sign. There is usually no lack of natural flour and grain dust deposited about an active grain storage or cereal processing plant, but in a finished-product warehouse, flour or talc dust may be applied to foot-square areas in the most

vulnerable parts of the building and regularly inspected for tracks. Because house mice have such a limited feeding range and may thrive in the center of a stack of sacked grain or flour with little or no observable damage to sacks on the exterior, the floor about the base of the stack should be repeatedly dusted and inspected for tracks. An ultraviolet light, the use of which will be explained later in connection with "detecting rodent contamination of products," may be used to detect rodent urine stains. A strong musky odor will identify a house mouse infestation of some duration. Greasy smears that are free of dust denote rat movements along overhead pipes and ceiling plates. It should hardly be necessary to mention rodent-torn sacks and broken packages, holes and gnawing in the building and equipment with the resultant scattering of chips, the occasional nest that is found as some little-used stock is moved, and soil burrows with new earth or clear, smooth entrances. Certainly the grounds about the building should not be neglected in this inspection. Here, burrows in the ground and well-worn trails in the weed and rubbish cover are ample indications of the presence of rodents.

Poisoned Baits

A poison is only as good as the bait that carries it. In other words, food, food odors, and liquids that satisfy hunger and thirst serve as carriers for the otherwise unpalatable toxic agent. The more attractive the bait, the more successful the control program is likely to be.

Selection of Bait Material. Ordinarily it is wise to select for baits foods not available among the stocks to which the rodent has access. Thus, in a grain storage or processing mill the use of meats, fish, fresh fruits, and vegetables is indicated. It is neither necessary nor practical to use these full strength; in fact, bulking one part of such bait with three parts of a cereal like dry oatmeal, yellow cornmeal, or dry bread crumbs is recommended. Liquid baits have proved very effective in controlling rat infestations because the normal sources of water for rodents in grain storage are either limited or wholly absent. Aqueous solutions or suspensions of certain poisons are well accepted. The addition of not more than 10% of sugar to the water sometimes improves acceptance. Milk and tomato puree are two other liquids that have been successfully employed.

There also are considerations other than the palatability of the bait selected. With solid foods, moist baits are generally better accepted than dry. But moist baits and liquids such as milk and tomato puree spoil rapidly in warm weather. If a more permanent type of food bait is required for use in protected stations, then a cereal base bait with sugar and an animal or vegetable fat is suggested (4a). Another consideration is the possible contamination of stored grains and cereal products

by poisoned baits exposed for rodent control. To prevent a rat from removing poisoned bait from an otherwise safe placement, the bait should be finely pulverized so that no large pieces can be dragged off to other parts of the building. In this regard, liquid baits are equally safe as they must be ingested where placed. Finally, there is the technical problem of choosing the bait to fit the poison, as the two must be chemically compatible for the purpose of toxicity and absorption (see Table I).

Selection of the Rodenticide. The species of rodent to be controlled will often dictate the poison that must be used. This is an extremely important consideration, for stored grain is often beset not with one but with several species of rodents. Of the rodenticides listed in Table I, arsenic, phosphorus, thallium, and sodium fluoroacetate and the anticoagulants are the only ones that will control a mixed rodent infestation of Norway rats, roof rats, and house mice with any degree of success. Red squill, ANTU, and barium carbonate are poor mouse poisons, and strychnine is a very poor rat poison. ANTU is roughly 50 times more toxic to Norway rats than to roof rats and thus has limited usefulness.

Two methods are used to expose poison bait for rodent control. One involves the thorough coverage of the premises with small pieces, or teaspoonful lots of baits, containing a poison that will kill in a single feeding. The residual bait, following 24 hours of rodent feeding, is usually collected and destroyed. The second method is the exposure of large quantities of bait in some type of covered container. Such placements are semipermanent and are serviced and refilled at regular intervals. Very few poisons can be used both ways. For example, rodents may develop a tolerance to certain rodenticides following nibbling or cautious feeding. Mice that survive their first contact with strychnine and have it available for repeated slow feeding may consume large quantities without harmful effect. Mice that live in the fields where arsenic sprays are used as insecticides often become tolerant to ordinary doses of this poison. A tolerance is also acquired toward ANTU, but more often avoidance is the chief factor in continued survival. Such tolerance is temporary and once the feeding on those poisons ceases it is usually lost within a month. These poisons are therefore unsuited for permanent bait stations. The same is true of red squill and zinc phosphide, which have such distinct taste or odor that they are shunned after a first feeding. Even sodium fluoroacetate, which has relatively little taste and is extremely toxic in small quantities, is often avoided following a sublethal feeding. Thallium sulfate is the only poison in the present listing that has possibilities both in single exposures and in permanent stations, and even it is far better in the former category.

TABLE I

COMMONLY USED RODENTICIDES AND THEIR CHARACTERISTICS (51, 59, 65)

Poison	Commercial Form	Source and Availability	Special Requirements for Use as Rodenticide
Barium carbonate	Heavy white cryst. powder	Mined & mfd. USA. Good.	Fine powder (ppt.)
Arsenic: arsenious acid	Heavy white cryst. powder	Mined & ref. USA. Good.	Toxicity increases with smaller particle size. Use 1 to 5 micron grind
sodium arsenite	As above	As above	Any refined powder
Strychnine: (31) alkaloid	Light, fine white powder	Tree seed grown in India & Malaya. Extract made in USA	Finely pulverized, refined grade
sulfate	As above	As above	Refined grade
Phosphorus: yellow	Yellow amorph. cryst. Spontan. combustible in air	Mined & ref. USA. Good.	Pulverized to micron size & suspended in syrup to reduce fire hazard
zinc phosphide (38, 56)	Heavy black cryst., stable when dry	Mined & mfd. USA. Good.	Refined grade, 325 mesh powder
Red Squill: (11) powder	Light reddish powder	Mediterranean plant bulb. Dried & pulverized USA	Free-flowing fine powder. Standard or fortified to 500-700 mg./kg. toxicity
extract	Dark syrupy fluid	As above	Standardized as above
Thallium sulfate (39)	Heavy, white cryst. powder	Mineral ores from Europe and USA. USA supplies limited. Ref. USA	Refined grade, 200 mesh powder
ANTU (Alpha naphthyl thiourea) (44)	White cryst. powder	Synthesized from chemicals readily available USA	Refined grade, finely pulverized
"1080" (Sodium fluoroacetate) (40, 50, 60)	Light, white cryst. powder	Synthesized from chemicals readily available USA	Refined grade
Warfarin (anticoagulant) 3-(alpha acetonylbenzyl) -4-hydroxycoumarin (12, 15)	Light, white cryst. powder. Commonly reduced to 0.5% in cornstarch	Synthesized from chemicals readily available USA	Refined grade
Pival (anticoagulant) 2-pivalyl-1,3-indandione (14, 16)	Bril. yellow cryst. powder (New)	Synthesized from chemicals readily available USA	Refined grade
Tomorin (anticoagulant) 3-(1′-parachlorophenyl -2′-acetylethyl)-4-hydroxycoumarin (13)	Tech. non-cryst. solid (New)	European source. Readily synthesized.	Pulverized technical powder

TABLE I (Contd.)

Poison	Toxicity & Acceptance of Baits Prepared at Listed Concentrations	Hazards Attending Use	Solubility in Water and Stability	Amt. Used in Baits by Wt.
Barium carbonate	Low toxicity—rats. Fair acceptance	Low human & secondary poisoning. Dangerous for domestic stock	Not soluble Stable	20%
Arsenic:				
arsenious acid	Adequate toxicity. Erratic acceptance, both rats & mice	Toxic to most life. No serious secondary hazard. Antidote available	Limited solubility Stable	1%-2%
sodium arsenite	As above	As above	Soluble, stable	1%
Strychnine: (31)				
alkaloid	Highly toxic. Acceptance adequate for mice only	Generally toxic, quick acting, warning bitter taste, antidote available	Not soluble Stable	0.5%
sulfate	As above	As above	Soluble, stable	0.5%
Phosphorus:				
yellow	Good toxicity. Acceptance good for both mice & rats	Generally toxic, low secondary hazard, warning garlic-like odor	Not soluble, oxidizes on exposure to air	1%
zinc phosphide (38, 56)	As above	As above—black color and odor warning	Not sol., hydrolyzes in presence of moisture	1%
Red squill: (11)				
powder	Relatively low tox. Acceptance adequate for rats only	Relatively nontoxic except for rats, emetic reaction & warning taste	Not soluble Stable	10%
extract	As above	As above	Miscible with water	10% or Mfg. recom.
Thallium sulfate (39)	Good toxicity. Acceptance good for both rats and mice	Generally toxic, cumulative, slow absorb., no warning, secondary poisoning occurs, no effective antidote	Limited solubility Stable	1.5%
ANTU (Alpha naphthyl thiourea) (44)	High toxicity for Norway rats only, acceptance adequate	Low human & secondary hazard, livestock endangered, no antidote	Not soluble, stable except at high temperature	1%-3%
"1080" (Sodium fluoroacetate) (40, 50, 60)	Highly toxic. Acceptance adequate for both rats and mice	Generally toxic, fast absorption, no warning, high secondary hazard, no antidote	Very soluble Stable	0.25%-0.5%
Warfarin (anticoagulant) 3-(alpha acetonylbenzyl) -4-hydroxycoumarin (12, 15)	Requires repeat feeding for few days to 2 weeks. Acceptance excellent for both rats and mice	Very low toxicity from single feeding, secondary hazard almost nil, antidote available	Low solubility (approx. 0.004%) Sodium salt adequately sol.	Food baits 0.025% Liquid baits 0.005%
Pival (anticoagulant) 2-pivalyl-1,3-indandione (14, 16)	As above	Same as warfarin. Has some insecticidal properties	As above	As above
Tomorin (anticoagulant) 3-(1′-parachlorophenyl -2′-acetylethyl)-4-hydroxycoumarin (13)	As above	Same as warfarin	Low solubility	Food baits only 0.025%

Operations involving exposure of warfarin, pival, and tomorin (12, 13, 14, 15, 16) should be continued over a period of 1 to 2 weeks to result in effective control of house rats and mice. Fortunately, at the low concentration that they are used in rodent baits (0.025%) they are readily accepted. The toxic symptoms develop so gradually that the rodent apparently does not associate them with the food to the extent that adequate feeding ceases. In other words, these three rodenticides are excellent for use in permanent bait stations and not effective in single 24-hour exposures.

The operator of a grain storage would do well to consider the rodenticide from the standpoint of hazard, as well as of efficiency. Red squill is reasonably safe for humans and domestic animals, in that it behaves as an emetic for all save rodents. The three anticoagulants also are reasonably safe in single feedings at the accepted rat bait concentrations, although a few dogs and cats are highly susceptible and have succumbed to single feedings of warfarin. Day-after-day (multiple) feeding on rodent baits by pets is not apt to occur accidentally. ANTU is reasonably safe for humans but has proved hazardous to dogs, pigs, horses, and baby chicks in rodent bait concentrations (44). Barium carbonate has to be eaten in such large quantities to prove toxic that it is usually considered in the low hazard category. All other rodenticides listed are dangerous to most forms of life, but there are ways in which the more toxic compounds can be made relatively safe. H. J. Spencer (49) has shown that combining the following rodenticides with designated amounts of an emetic protects dogs and cats from as much as five times the ordinary lethal dose.

Zinc phosphide	8 parts: tartar emetic, 3 parts
Thallium sulfate	7 parts: tartar emetic, 4 parts
Barium carbonate	140 parts: tartar emetic, 3 parts
ANTU	2 parts: tartar emetic, 1 part

The speed of absorption of sodium fluoroacetate is so great that the above emetic offers no protection against the toxic action.

It is possible also to expose a very toxic poison in permanent bait stations that are so constructed that no person or large animal has access to it. However, there is no assurance that the rodent that has been poisoned will die in an equally inaccessible place. Furthermore, poisoned rats sometimes are gathered, placed in garbage cans, and through that channel find their way to pig farms where that garbage is fed. Examination of Table I will show that both thallium sulfate and sodium fluoroacetate have a secondary poisoning hazard, a hazard that continues to exist months after the poisoned rodents have become dried carcasses. Sodium fluoroacetate is almost 50 times as toxic to a domestic dog as

to a rat, with the result that eating one rodent may prove fatal (50, 60). Zinc phosphide, on the other hand, has little secondary hazard, for it is rather uniformly toxic to mammals on the basis of their weight. In addition, zinc phosphide is largely detoxified in the body of its first victim. Toxic phosphorus compounds are generally unstable and tend to lose their poisonous properties with the length of bait exposure. Red squill and the three anticoagulants can be said to have no secondary hazard.

Several other devices are employed to protect humans and beneficial animals from accidental poisoning. The marked taste of such rodenticides as red squill and the color and odor of zinc phosphide are natural warning features. The use of color is now extended to many white crystalline poisons. For example, nigrosine black dye is presently used to discolor sodium fluoroacetate. Pink is often used with arsenicals, green with thallium, while pival is a natural brilliant yellow. Kalmbach and Welch (33) invoked the color protection principle when they demonstrated that many birds, including the domestic pigeon and chicken, have an aversion to unnaturally colored foods. Thus poisoned grains dyed an unnatural hue were either avoided or fed upon so lightly that little harm resulted. The deterrent value of color is lost on too regular or frequent exposure. Useful as odor, taste, and color may be for informed adults, they offer little in the way of protection for small children and domestic mammals, the latter being largely if not completely color-blind.

Liquid baits have been used for years in the United States to control rats, but reached a high popularity with the introduction of sodium fluoroacetate. Water may be had without cost, the solutions are simple to prepare, and the efficiency of rat control thereby compares favorably with that of any food bait prepared with a similar rodenticide. Sodium arsenite, thallium sulfate, and sodium fluoroacetate (listed in order of increasing effectiveness) and the new anticoagulants, warfarin and pival, are the poisons so used. Sodium fluoroacetate at 12 g. to 1 gal. of water is the most toxic, and, largely because so little of the poison solution need be taken, is a very effective control agent. The outstanding rodenticide for liquid baits will likely be pival because of its stability, excellent acceptance, and freedom from secondary hazard. Liquid warfarin baits have proven effective under field trial, but solutions of the sodium salt tend to mold, with subsequent loss in acceptance. ANTU should be mentioned at this point, for while it is not soluble, it can be dusted as a thin film on the surface of water and thus becomes a fairly effective water-carried poison for control of Norway rats.

With water, no cautious "new food" reaction is involved; thus it

may be very successfully employed without the necessity of prebaiting. Actually, solutions of sodium fluoroacetate are credited with reducing to the lowest point in history the mixed rodent infestations in the towns and cities of southeastern United States. It therefore appears that liquid baits should be particularly effective in grain elevators and warehouses with their stocks of dry food. However, of the foregoing, *three* rodenticides that are effective in water solution are highly toxic, especially thallium sulfate and sodium fluoroacetate. Their careless use about food-handling establishments would be actionable under law. There is sufficient poison in ½ oz. of sodium fluoroacetate solution at the stated formula strength to kill a small child. Even if the solution has evaporated to dryness the residue adhering to the cup is still a hazard to children who may play with it. There is every reason, therefore, for the utmost caution if thallium sulfate or sodium fluoroacetate is employed about grain storage. The two anticoagulants are best for food-handling establishments.

The use of dust or tracking poisons is an intriguing field of rodent control, for it eliminates the necessity of getting the rodents to eat a poison carrier. A powder dusted into the rodent burrows, between double walls, along runways is picked up on the feet, fur, and tail of the rodent. In cleaning themselves, the rodents inadvertently ingest the poison. ANTU powder bulked with four parts of talc has been successfully used in this manner for the control of Norway rats. A micronized DDT (insecticide) used as a 50% dust has been reported favorably in the control of house mice. No compound other than one with a low human hazard and a correspondingly high rodent toxicity should be employed in buildings in this manner because of the chance of food contamination. But, even then, the dust rodenticides would be tracked over sacked grain, flour, and other foodstuffs between the time of rodent contact and the delayed ingestion and death. It is therefore recommended that dust application of rodenticides be not employed around stored grains and cereal products.

Preparing Food Baits. The rodenticide, if insoluble, should be obtained in as finely divided a powder as possible; for not only does this facilitate the distribution through the bait mass, but, as with arsenic, coarse powders are somewhat less toxic. If the amount of poison called for in Table I seems inadequate to cover the bait evenly, it can be bulked with wheat flour, cornstarch, or magnesium carbonate and then worked into lightly oiled whole grain or mash or dusted over fresh-cut fruits and vegetables. If any fluid such as a vegetable oil or syrup is to be mixed with a cereal base bait, then it is often advantageous to suspend the powdered poison in that fluid before adding it to the dry base. A little

color pigment added to the dry powder, or dye to the fluid-suspended poison, will serve as a tracer to insure even mixing of the bait and poison. It is not necessary to impregnate whole grains with a poison. In fact, it is advantageous from the standpoint of rodent acceptance to coat the toxic materials on the outside of the kernels. For this purpose, starch pastes to which a little syrup or glycerin is added, soybean lecithin, certain oils, and some new cellulose compounds are satisfactory carriers and adhesives for either soluble or insoluble formula ingredients.

Oils and fats used in permanent type baits often become rancid, and acceptance by rodents is thereby impaired. The addition of an antioxidant, like that derived from wheat germ, will delay this deterioration. The life of fresh fruit and vegetable baits may be prolonged by immersing the poison-treated cubes in a warmed mixture of 80% paraffin and 20% mineral oil, then draining. Attempts at adding antifreeze preparations to liquid baits have resulted in failure because rodent acceptance decreased.

Bait Handling and Placement. The reaction of rodents to new foods or to new placement of an accustomed food, mentioned under rodent behavior, presents a problem in bait acceptance that grows more difficult with each succeeding attempt at poisoning. This may be overcome by one or a combination of several devices. First, the effectiveness of baiting is greatly enhanced if the normal sources of water are eliminated or covered, or if the natural food supply is curtailed by better housekeeping. Second, multiple bait spots, conveying a variety of two or three highly attractive foods, may be exposed at the same time. Third, use may be made of a highly toxic compound in bait concentrations such as would require very little feeding to cause death, thus affecting even the "nibblers." Fourth, there is prebaiting, a practice of exposing token amounts of proposed food baits in selected feeding sites for a variable period of time before poison is added. Prebaiting overcomes the rats' wariness of new foods and new placements. It results in training the rodents to anticipate and look for the bait placement, and to eat rapidly of the food supply under press of competition. The experiments conducted by Thompson (55) are an excellent illustration of the response of wild Norway rats to 4 days of prebaiting before that same food was treated with poison on the fifth day. In Figure 3, note how the bait offered was cleaned up earlier and earlier each night, so that in less than 1 hour after the placement of poisoned bait on the fifth day every rat had fed.

The speed with which a rodent ingests poisoned food is of paramount importance with most toxic chemicals (other than the anticoagulants). Some poisons are rapidly absorbed and result in toxic symptoms within

as short a time as 15 minutes. If the rodent, wary of a new food, follows its usual feeding pattern of cautious nibbling, then the toxic action may interrupt the feeding before a lethal dose has been ingested. Once an animal has been sickened by a sublethal dose of poisoned bait, that particular food bait may be avoided for months, even though the poison it contains in subsequent control programs be changed (4). Prebaiting unquestionably improves the effectiveness of a poisoned bait program, and is perhaps the only solution where various rodenticides have previously been employed with indifferent results.

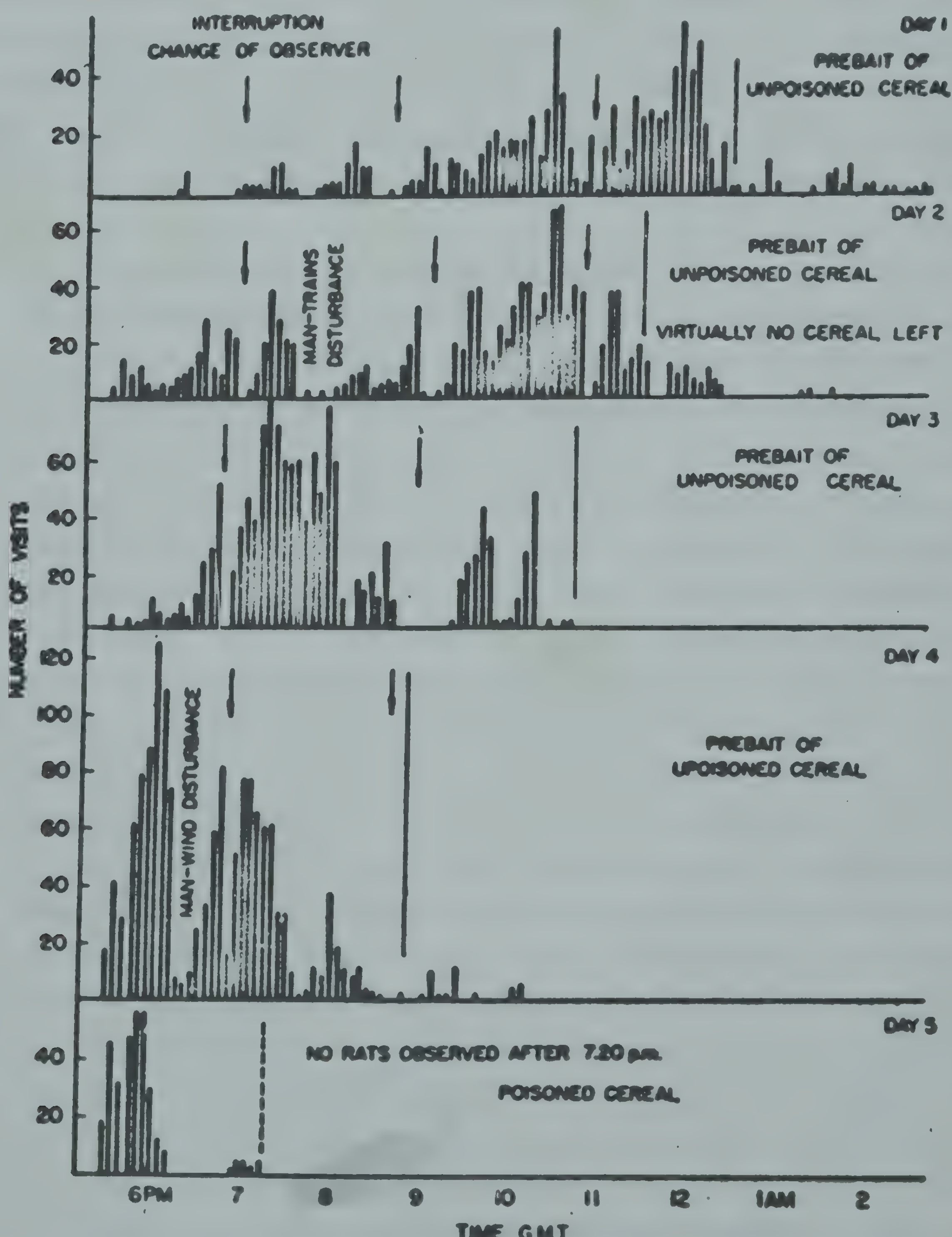

Fig. 3. A record of the number of visits by Norway rats to food exposed in their natural habitat. Illustrates the effect of exposing food for several nights to overcome the wariness of rats to bait acceptance. Note particularly that the feeding becomes earlier and more intense. Reproduced from studies at the Bureau of Animal Population, Oxford University, by Harry V. Thompson (55).

The single effort method of rodent control employs poisoned baits of small size, one tablespoonful of food or ½ oz. of fluid, distributed in multiple placements throughout the building and grounds. Baits may be dropped into burrows, placed along trails that are under cover, or put in dark corners and in other obscure places frequented by rats. Be thorough in covering the area and always use more bait and placements than are deemed necessary. After a period of 48 hours, collect and destroy by burning all dead rodents, all poison bait residues, and any disposable bait receptacles. This program of small bait distribution makes use of several convenient methods of handling poison materials. One practice is to wrap each solid food bait by placing it in a 6-in. square of thin paper and twisting into a torpedo shape. The moisture or oils used in the bait soon soak to the outside and incite the rodent to cut into the torpedo. Wrapping serves to keep the bait clean and speed up placement around waste dumps, trash piles, and burrows. Liquid baits are commonly distributed in small, squat, ½-oz. paper cups. A non-tipping, disposable shallow dish, designed and labeled for exposure of poisoned liquids is available on the American market.

All baits placed in the *vicinity of grain or food storage* should be liquid or finely ground so that there are no wrapped or sizable pieces that can be removed from an otherwise safe placement. Secondly, every precaution must be taken to insure that poisoned baits are not placed adjacent to, on, or above grain and cereal products, so that if spilled from their container, the food might become contaminated. It is worth emphasizing here that in the Food, Drug, and Cosmetic Act in the United States, the expression "may contaminate" is used; furthermore, contamination need not be in toxic quantities. Thirdly, when open exposures are made at a safe distance from food, containers that cannot be moved or tipped should be used. For example, a heavy glass castor may be substituted for the paper dish. Lastly, in any room where grain or cereal is stored or processed, poisoned baits must be used only in covered, locked, permanent bait stations.

Permanent bait stations (Fig. 4) should be used to expose anticoagulants that must be offered in quantity and over a period of time. They may be of many different types and shapes to suit the materials and the desires of the operator, but they should embody the following characteristics: (a) be constructed of materials sturdy enough to withstand activities typical of a given room, (b) be firmly affixed to the floor or wall, (c) be equipped with a lock to prevent meddling by irresponsible people, (d) be plainly labeled POISON, (e) have two or more rodent entrance holes 3 in. in diameter, and (f) be roomy enough to fully accommodate the largest rat from either direction. Baffle plates on

the interior of the box, as shown at C in Figure 4, are desirable when used in areas outside a building. This box has an outer measurement of 20 by 12 by 8 in. All such stations should have the bait pan or liquid dispenser fastened in position near the center. Baits used in stations should be inspected at intervals frequent enough to prevent loss by spoilage or evaporation.

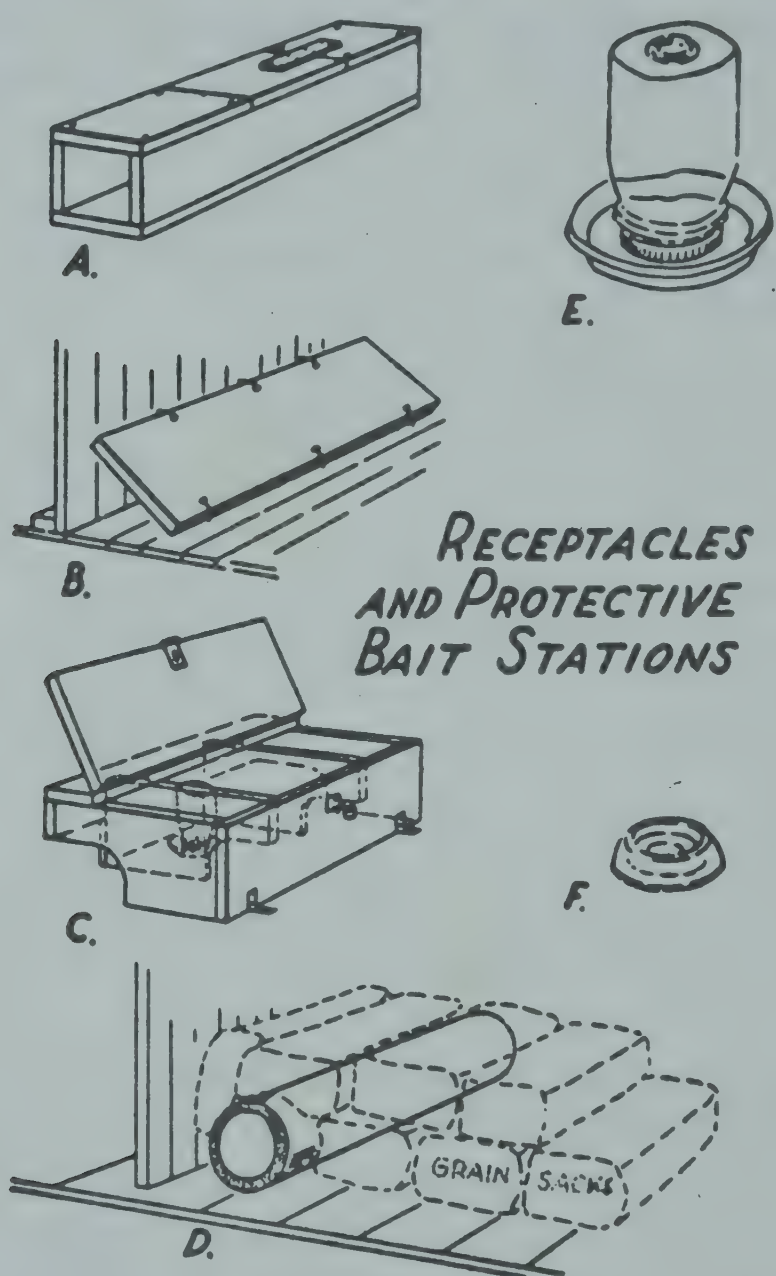

Fig. 4. Various types of protective bait stations (A to D) and liquid bait dispensers (E and F).

Trapping

Trapping has its limitations, yet can be a highly effective means of maintaining a rodent-free grain storage. While the method is limited to minor infestations within a building it avoids most of the hazards in the use of poison about a food-handling establishment. Rat and mouse traps vary from the simple "breakback" or animal steel trap costing but a few cents, to elaborate mechanical and electrical traps costing several hundred dollars each. The secret of success in trapping lies not so much in the style of trap, nor in its cost, but in the operator's under-

standing of rodent habits. Earlier in this chapter the "new object reaction" of rats was mentioned. Anything strange, even a simple block of wood placed in the runway of a rat, was avoided at first. A trap has the same handicap. As for baited traps, they represent both a "new food" and a "new placement." The solution lies in using the trap to block the use of burrow openings or to block convenient and necessary trailways. The simplest of all rat traps is the wooden base snap trap, measuring roughly 7 by 3 in., pictured in Figure 5. It is not necessary to handle these traps with gloves or to smoke, wash, or clean them to remove human odor. If oiled and kept in good working order and free from caked blood of rodent victims, they constitute the best trap money can buy. A $2\frac{1}{2}$ in. square piece of corrugated cardboard or thin plywood should be attached to the trigger as illustrated. This broad enlarged trigger will reduce the weight necessary to spring the trap so that it will catch the largest rat or the smallest house mouse equally well. Finally, the trap should be set where the rat cannot avoid it if he must use a given hole or runway. No bait is required.

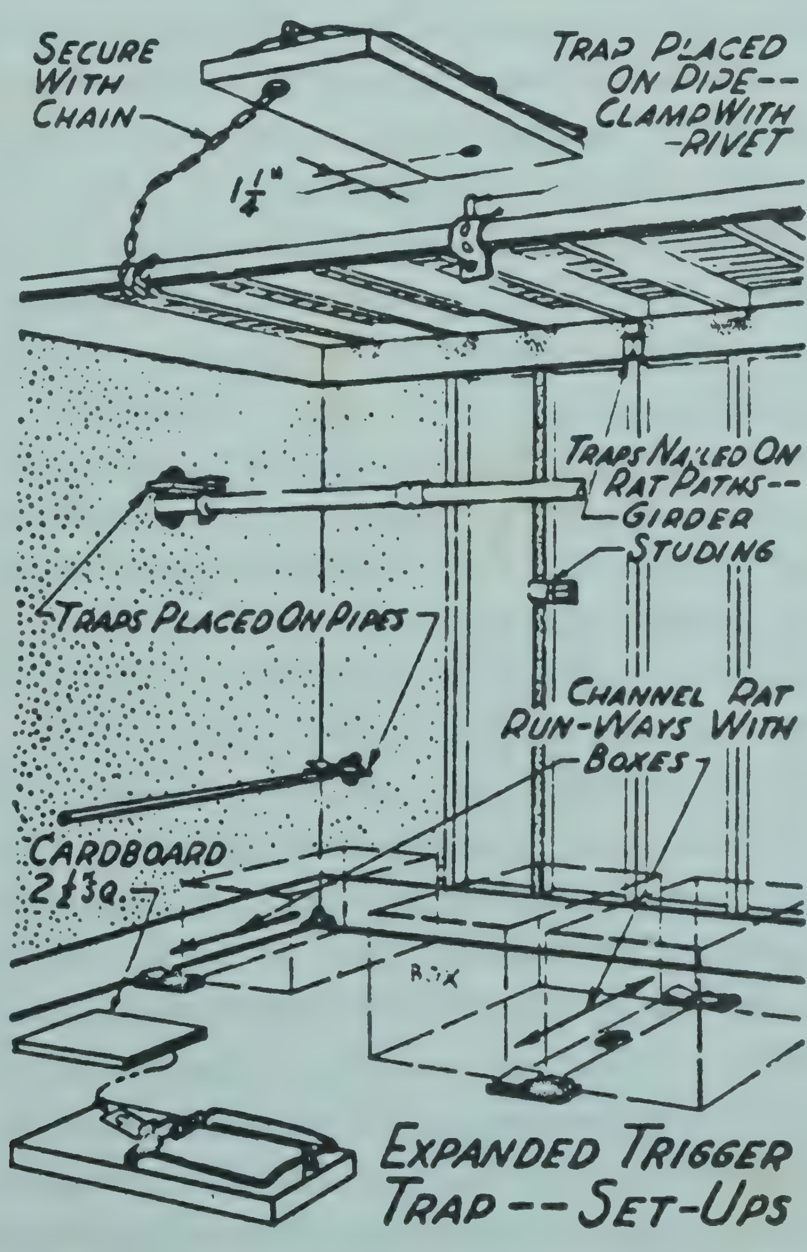

Fig. 5. Correct use of the common snap trap in rat control.

Illustrated in Figure 5 are the correct placements for wooden base snap traps. On the floor, along the wall, the rat can be forced across the trap by making the set only at points where the runway passes between a permanent piece of equipment or a box moved into position to create a tunnel. Note that the trap is set at right angles to the runway so that only the expanded trigger is in the path of the rat. A low block of wood placed an inch or so to one side of the trap makes the barrier too wide for the wary rat to jump across the trap. In other words, the rat is outmaneuvered. When rats are gaining entrance to a room through holes in the corner or floor, similar walled-trails can be created by moving boxes into position and then setting the traps as described above. A hole can be drilled in the forepart of the wooden base and thereafter the trap fastened by nail or screw to many wall and overhead positions. Figure 5 shows the trap in place on an upright studding on which greasy smears identify a climbing travel route for rats. Also shown is the trap in place along the ceiling plate where the rat swings below each rafter in passing. These are excellent sets, for the rats cannot jump over the trap. Lastly, there is the very useful pipe set. A metal spike, ½ in. high, is attached to the top of the pipe by means of a garden hose repair clamp for the smaller pipes or a piece of strap iron for the larger ones. The spike may be made from an upended rivet or a nail that has been cut off to the proper length. About 1¼ in. in from the front of the trap, drill a hole to receive this spike—a hole that fits snugly but not tight. Now place the enlarged trigger trap on the spike and set. If the pipe, along which the rats are traveling, enters through a hole in a division wall, then set the trap on the pipe immediately in front of the hole and thus forestall any attempt at jumping over the trap. The trap should be wired to the pipe by a flexible loop from the rear of the trap. When sprung by a rat the trap will ordinarily bounce off its spike and hang by this wire a couple of feet below with its victim. Other rats can then continue to use the runway until the victim is removed and the trap reset. Note that the last three trap sets are all overhead, well out of the way of workers and normal operation. Such permanently set traps should be distributed throughout any grain storage building or warehouse, not only to catch resident rodents, but to forestall any invasion of a rat-free premise. Traps catch invading rats quite readily, for the "new object" reaction is dulled by the circumstance of migration.

Southern and Laurie (47) state that the house mouse exhibits little if any "new object" hesitancy, and certainly it is much easier to trap. Either the large expanded trigger rat trap or the smaller mouse trap may be used. Set the traps in a blocking fashion along floors and shelves, much after the fashion illustrated for rats; but, in addition, baits will

be found advantageous for taking mice. Use a dry cereal to which some attractant has been added, like a little fat from meat fryings, or syrup, but just enough to lend scent and odor. Dried cake or cooky crumbs make good bait. From a position about 4 in. above the trigger of the trap, sprinkle a half teaspoonful of this bait. Some of the crumbs will fall on the trigger, some around the trigger, and some on the floor beside the trap to serve as prebait. The mouse will step on the trigger in course of feeding.

In actual practice it has been found that one of the most serious obstacles to success in trapping is lack of proper maintenance. Traps should be examined at regular intervals, rodents removed, traps otherwise serviced, and new blocking trap sets made when other rodent sign is noted.

Poison Gases

General fumigation for insect control (Chapter V), whether in a canvas-covered stack of unthreshed grain on the farm or in the sealed building of a large grain elevator or warehouse, is equally effective in rodent control. In fact, if rodent control were the only objective, the amount of fumigant per cubic foot of storage space could, in some cases, be reduced to half the quantity employed for insects.

The fumigation of the burrows of the Norway rat is an effective and economical method of control. Since the work is performed outdoors, and with applicators specifically designed for the purpose, there is little hazard for the operator and no special training or licensing is required. Cyanide (1) is one of the most widely used materials for this purpose, and is available as calcium cyanide in a fine gray powder, small granular crystals, or flat flakes. The dust form is blown into the burrow by means of an inexpensive hand or foot pump, while the granules and flakes are deposited in 1- to 2-oz. quantities, well down in the burrow, by means of a long-handled spoon. The burrow openings should be closed after the gas application. Carbon disulfide is a heavy, malodorous liquid that is commonly used in field control of rodents in the United States. A special pump is available that measures the required 1- to 2-oz. dose and atomizes it into the burrow, although the older method of absorbing the liquid on balls of cotton waste (or other absorbent material) and rolling these down the burrow is still in use. Carbon disulfide is flammable and easily ignited so it should *not* be used for burrows extending under a building or in fumigating wooden bins and structures on the farm. Methyl bromide (5) (with special applicator) and chloropicrin are two other useful gases for burrow fumigation. Very recent research (30) has revealed that carbon monoxide is perhaps the most suitable gas for burrow fumigation, as it is highly toxic, nonexplosive, and affected

very little by moisture and absorption by soil colloids. A pyrotechnic cartridge of this type has been developed but is still not available.

Miscellaneous Methods of Rodent Elimination

Many a grain storage, mill, and warehouse places a considerable portion of the responsibility for rodent control on domestic dogs and cats. There can be no argument that a well-trained dog or an occasional cat is instrumental in killing rats and mice. Unfortunately, as there are often too many refuges for rodents in grain storage where the predator cannot follow, this method is far from effective. Furthermore, many dogs and cats have little interest in the rodents about them, and only serve to intensify the sanitary problem of storage by bedding on the foodstuffs, and contributing their hair and fecal wastes to the product. Ferrets have often been employed for rat control in buildings. They cannot be turned loose; the trainer or owner must work with them. The method is more of a sport than a practical and effective control and its use is not advised.

From time to time the use of rat viruses is exploited. The claim of spreading a contagious disease among the rats is intriguing but ill-founded and erroneous. The bacteria most commonly used belong to the *Salmonella* group, which cause food poisoning. The hazard of contaminating human or livestock foods is appreciable and therefore their use is prohibited by a number of state governments in the United States. Their use about a grain storage or cereal-processing plant is strongly censured.

Chemical repellents applied to structural materials to keep rodents from gnawing, repellents applied to bags, cartons, and cereal packages of all types to reduce rodent loss, and repellents mixed with insulating materials to keep rats from bedding in double walls are all subject to current research in both governmental and private laboratories (64a). At the time this is written, little has been accomplished in the way of their practical introduction into use, and J. F. Welch (61, 62, 63, 64) points out that the problem is a particularly difficult one. A rodent, in using its protruding incisor teeth to cut through a wall or into a food box, does not necessarily bring the chips from that gnawing in close contact with the mucous or absorptive surfaces of the mouth, and thus reduces the potential effectiveness of a taste repellent. A highly toxic repellent could not be used on food packages, and an odor repellent would be absorbed by any number of human foods, including flour, and might render them unmarketable. A change in the physical character of the package, which increases the hardness of the surface, has proved of some value in lowering rodent penetration.

Government Regulations Pertaining to Rodent Infestations

The ordinary business incentives are sometimes insufficient to cause the adoption of adequate measures for rodent control. Most nations have found it necessary to enact legislation that gives authority to some branch of government to enforce sanitary measures against rodents. For the most part, these laws are associated with public health and serve in times of disease crises. In the United States, in addition to public health regulations at various governmental levels, authority has been granted to the Food and Drug Administration, through the Food, Drug, and Cosmetic Act of 1938, to control the sanitation in these industries. The specific wording of the law dealing with this phase of the Food and Drug Administration's duties is contained in Section 402 (a) (3) which states that a food shall be considered adulterated "if it contains in whole or in part any filthy, putrid, or decomposed substance, or if it is otherwise unfit for food," and under Section 402 (a) (4), "if it has been prepared, packed, or held under insanitary conditions whereby it may have become contaminated with filth, or whereby it may have been rendered injurious to health." Section 404 further grants authority to the Federal Security Administrator to establish an Emergency Permit Control over an industry when it is shown "that the distribution in interstate commerce of any class of food may, by reason of contamination with microorganisms during manufacture, processing, or packing thereof in any locality, be injurious to health. . . ." "Filth" has been variously defined as any substance foreign to the proper composition of the product. Furthermore, no sections of the Act dealing with adulteration call for, nor in fact allow, tolerances in any amount for rodent filth contamination (29). Thus, it will be realized that with such legislation, millers and processors of cereal products in the United States rate rodent contamination as the most serious aspect of the entire rodent problem.

In recently enacted legislation, the United States Department of Agriculture, through the Insecticide, Fungicide, and Rodenticide Act of 1947, requires the registration of rodenticides before they may move in interstate commerce. While this has no direct bearing on the cereal processor, it assures him that nationally distributed products will conform with the manufacturer's claims as to analysis and general performance.

Methods for Detecting Rodent Contamination of Cereal Products

The first consideration is, of course, the gross examination of the product, and its immediate environs, for rodent sign, tracks, excreta, urine stains, and gnawing. The excreta of rats are distinctive by their size and shape, but those of mice might be confused with excreta of

insects like the cockroach. Rodent excreta can be distinguished from insect excreta by the mucuslike coating that even in a finely comminuted condition appears as a grayish-white layer when moistened. Whole excreta and large fragments are recoverable by sifting the flour through a 30–50 mesh screen. In addition, signs of gnawing on containers and feeding on grains (51a) or on cereal products like macaroni are easily distinguished by the parallel indentations spaced by sharp ridges that are the marks of the twin incisors. Burlap or cloth bags are ragged and frayed at the edge of rodent-cut holes. Cardboard cartons, or similar containers, often bear greasy smears, rubbed there from the rodent fur, about the edges of the gnawed entrance hole. Urine stains as light irregular discolorations are apt to show on the surface of the grain and flour sacks. Urine also causes caked masses in flour. In preliminary examinations, "black light" or, more correctly, ultraviolet radiation will prove valuable. Urine, upon drying, leaves substances that fluoresce with a whitish to greenish light when exposed to ultraviolet light. Certain fats, oils, and other products commonly found around a cereal-processing plant also fluoresce, so for positive identification it still may be necessary to remove a portion of the material with the stain and forward it to a chemical laboratory for analysis.

Buckley and Whinery (6) have devised a simple spot test for urine that may be used at the scene of investigation. "Three grams of paradimethylamino benzaldehyde are dissolved in 25 ml. of ethyl alcohol and made up to 100 ml. with a saturated solution of oxalic acid. By applying this solution to a suspected urine stain with a camel's-hair brush, a chrome yellow color will develop if urine is present. This test works well on cotton, paper, and burlap bags."

Gross examinations like those described above will often fail to reveal rodent contamination that has been finely divided in the course of processing the grain into flour and similar products. Microanalytical methods are required that necessitate considerable training and skill (29). Except in large concerns that maintain their own chemical laboratories and trained staff, the products to be examined for possible microscopic rodent filth should be sent to some qualified consulting laboratory. Solely for the purpose of illustrating the skill and technics involved in a filth determination of this type, a few of the methods employed may be mentioned.

With products like flour it is possible to separate and float off the plant material so that the rodent excreta is concentrated. A sample of the contaminated flour is suspended in chloroform. The rodent pellet fragments will settle out and the flour will float and may be decanted. Should the cereal product be of such a type that troublesome amounts

of bran or other plant material settle with the rodent excreta, then the specific gravity of the solution can be increased by adding carbon tetrachloride, but at no time should the amount of this latter more than equal that of chloroform, or certain of the heavy rodent filth will also float.

TABLE II

Comparison of Rodent and Cat Hairs for Microscopic Determinations
Taken from "Microanalysis of Food and Drug Products" (29)

Character	Rodent	Cat
Medulla (fur hair)	Single-rowed, discontinuous	Single-rowed, discontinuous
Medulla (guard hair)	Multiple-rowed, discontinuous	Smooth or erose, continuous
Internodes	Prominent or a few indistinct	Indistinct
Diameter	Usually smaller	Usually larger
Cortex size in relation to medulla	Usually narrow	Usually wide
Cortex pigment	Usually sparsely scattered or absent; none when none in medulla; pigment granules in scattered rows	Usually abundant; may be present when medulla is unpigmented; granules often in dense parallel rows
Cuticular scales of guard hairs	Ovate, elongate to flat; some very ovate elongate present	Crenate to flat; some very flat present
In NaOH: Medulla pigment	If present, usually compact, black or dark brown; often localized at one end of segment with other end clear, or at both ends with center clear	If present, composed of loosely scattered granules; granules brown or reddish, seldom black or dark brown
Shape of medulla segment	Usually long in direction of hair elongation; usually have hourglasslike constriction	Usually wider than long; sometimes have hourglass-like constriction
Distance apart of adjacent medulla segments	Usually relatively far	Usually relatively close
Contact of adjacent segments	Often squared across	Usually ball-and-socket effect
Cortex appearance	Usually has a clear gelatin-like appearance	Usually not clear, and with faint parallel, longitudinal lines
Cortex—in hypochlorite, NaOH, or untreated	Usually not heavily pigmented	Usually abundantly pigmented, with dense pattern of pigmented granules arranged in broken parallel rows

A second method of separating microscopic filth from flour is by the use of saturated-salt gasoline-flotation in a Wildman trap flask (2). The specifications follow: "Weigh 50 g. of flour into a 250 ml. beaker. Add *ca* 60 ml. of 10% pancreatin soln. diluted with an equal volume of water and stir into a smooth paste. Add *ca* 40 ml. of 10% pancreatin soln. (100 ml. total) and mix. Adjust pH to 7–8 with trisodium phosphate soln. and digest at 40°C. for 3 hours. Transfer digested material to a liter size Wildman trap flask. Add 20 ml. of gasoline and mix thoroughly. Allow mixture to stand 5 minutes and then fill with saturated sodium chloride soln. and after 30 minutes trap off into a 250 ml. beaker. Add *ca* 10 ml. gasoline to the material in the trap flask and stir into the mixture. Five minutes thereafter trap off into the same 250 ml. beaker. Transfer the total contents of the beaker to a trap flask and fill with saturated sodium chloride soln. Stir, and after 30 minutes trap off into beaker and filter through rapid filter paper, using suction. Examine microscopically. Screen the remaining contents of the first flask through a 40 mesh sieve. Wash the larger particles into a white enamel pan to recover any rodent pellets or lumps or heavy filth which may have settled to the bottom of the flask."

Once the filth particles have been segregated they are ready for examination under a microscope, the best being a Greenough-type stereoscopic. The recognition of small fragments of plants, insects, and animal filth requires the experience and training of an expert. Small pieces of rodent excreta, for example, can be positively identified only by the fragments of rodent hairs, which the animals ingest in the process of cleaning themselves. Rodent hair occurring in the excreta are of three different types, which further complicates the identification. Hairs of man, dogs, cattle, and many others are easily distinguished from those of rodents, but there is an irritating similarity in the hairs of rodents and those of the common house cat. The distinguishing characteristics used to separate these two classes of hairs are given in Table II. This further emphasizes the need for competent laboratory assistance when attempting microanalysis of filth in food.

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CHAPTER VII

Country Storage of Grain

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Much grain is lost every year in the United States as well as in other countries because of inadequate methods of storage and handling. Protection against such destructive agents as weather, insects, rodents, and microorganisms is necessary to maintain the condition and quality of grain. The final value of grain largely depends upon the protective measures employed, and these vary somewhat with the kind of grain, climate, and available facilities. Aside from terminal elevators, which are discussed in the next chapter, storage facilities in the United States and most other countries comprise farm granaries and corn cribs, and similar but larger facilities owned by the government. Country elevators, in which grain is collected at country points for shipment to terminals and processing plants, are peculiar to the North American continent, but add enormously to storage capacities. Some special types of storage, such as gastight and underground, must also be considered; and to these must be added the most expedient but temporary type of storage, namely, mere piling of the grain on the ground.

These various kinds of rural storage are discussed in this chapter. The first section is devoted to general consideration of conditions required for safe storage of grain and the functional requirements for the storage buildings. Bins and similar structures used for the storage of small grains and shelled corn are then considered; this discussion covers both farm granaries and the similar, though often larger, structures owned by the government. Since ear corn presents special problems it is considered separately. A further section deals with country elevators, and is followed by a final section on special types of storage.

General Considerations

No matter what the type of storage, there are certain general requirements that must be fulfilled if the grain is to be safely housed and if its quality is to be maintained. While many of these requirements are

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well known, it seems desirable to summarize them before undertaking more detailed discussion of various types of storage. The requirements may be divided into three main groups that relate to: the condition of the grain itself; the functions of the storage building in maintaining the condition of the grain; and the structural requirements of the building. These matters are discussed in the following three subsections, to which a fourth subsection has been added to deal with the pressures in grain bins.

Conditions for Safe Storage. Wide experience and extensive research on the storage of grain (19, 21, 32) have shown that its moisture content and temperature are the principal factors in safe storage. In addition, cracked grain and foreign material, if present in excessive amounts, also become factors in storage (14).

The maximum moisture content at which grain can be stored safely depends on the kind of grain, the locality in which it is stored, the methods of conditioning, and the length of the storage period. Wheat may be stored safely for a year with a moisture content about 1% higher in North Dakota than in Kansas, because the mean air temperature in North Dakota is about 10°F. lower during the summer (21). Shelled corn may be stored during the winter in the Corn Belt at a moisture content as high as 18%, provided the mass or bulk is not too large. Cribbed ear corn can be stored with moisture contents as high as 21% during the winter months (30). The outside air circulating through the cribbed corn keeps it cool while it slowly dries.

The maximum moisture contents for safe storage of several grains in farm-type bins for a period of one year in the principal grain-growing areas in the United States (6, 14, 21, 32) are as follows:

Kind of Grain	*Moisture Content* (% wet basis)
Shelled corn, oats, grain sorghums	13.0
Wheat (Hard Red Winter)	13.0–13.5
Wheat (Soft Red Winter)	13.0–14.0
Wheat (Hard Red Spring)	14.0–14.5
Soybeans	11.0

For grain stored as seed stock, or for long-time storage up to 5 years, the moisture levels should be 2% lower.

The range in the maximum moisture content for each of the different kinds of wheat is due in part to variations in the prevailing temperature in the regions in which the grain is stored. But some of the differences between one kind of grain and another are attributable to the different equilibrium relative humidities of different grains at the

same moisture content. These equilibrium values are important since Semeniuk (29) and others (see Chapters III and IV) have shown that molds will not develop below a relative humidity of 65%. This finding is in excellent agreement with the wide experience, and the many studies on the storage of grains, upon which the moisture limits in the above table are based. The lower moisture content for soybeans can be attributed to the fact that at a moisture content as low as 11%, soybeans are in equilibrium with air at a relative humidity of 65%. For shelled corn a moisture content 2% greater is required to produce the same relative humidity (6).

The moisture content of grain is also an important factor in the activity of insects (39). When it is as low as 9% in shelled corn and wheat, most of the destructive insects become inactive (5). While such low moisture contents are not readily obtainable in current practice, experience shows that the drier the grain the less the hazard from insect attack.

Another important factor is the temperature of the stored grain. When grains in storage are cool, there is less likelihood of spoilage. Low temperatures offset the effects of high moisture with respect to the hazards of mold growth and insect development. This is the reason why grains in cooler climates can be stored safely at a moisture content 1 to 1.5% higher than in warmer climates (21). One of the greatest benefits of the widely accepted practice of moving and turning grain in elevators is the cooling effect. Moreover, the recent and rapid adoption of methods of cooling stored grain by mechanical ventilation makes it possible to extend appreciably the safe storage period of high-moisture grains (28).

Ventilation or aeration of stored dry grain is not considered necessary in the conventional types of storages, except to cool the grain in cold weather and to prevent the migration of moisture to the upper layers (14, 21). Ventilation of the space between the grain surface and the roof is helpful in removing some of the excessive moisture accumulations in the upper layers and in removing excess heat in hot weather. Other than this, ventilation of stored dry grain is not necessary to keep it in condition. Under extreme humid conditions, it is detrimental because moisture will be added to the grain.

Cracked grain and foreign materials in excessive amounts are also considered to be an important factor in storage, especially as they provide favorable conditions for the development of the "nonboring" type of stored-grain insects popularly known as bran or fungus beetles (14, and Chapter V). These do not develop readily in clean grain but feed primarily on grain dust, broken kernels, and molds. Moreover, it is extremely difficult to fumigate grain which has a high percentage of

cracked and broken kernels and foreign material.

Functional Requirements. Before considering the storage methods and structures ordinarily employed, not only on farms but also in elevator storages, a brief discussion of the functional requirements for good storage is in order. These have been stated comprehensively by Stahl (35) in a publication of the U.S. Department of Agriculture. They are as follows: to protect the grain from excessive moisture, from insects, and rodents, and from temperatures favorable for both insect and mold development; to confine or hold the grain in bulk; to provide convenience and safety while moving grain in and out of storage; to furnish facilities for inspecting the grain without removal from storage; and to provide means for conditioning the stored grain.

One of the most important functions of a storage is to protect the grain from moisture increases above the safe storage limit, because as already indicated, moisture in excess of the safe limit is the predominant cause of spoilage. Therefore, the storage must give sufficient protection from the weather to keep out moisture. Although in storing dry grain, minor roof and wall leaks will not damage any appreciable quantity of grain, such damaged portions often become the sources of insect infestation and may affect the final grade if not segregated carefully when the grain is taken out of storage. In the storage of damp grain, such leaks are likely to start heating of the entire bulk or mass, thereby causing serious damage. The floors of grain bins, if in contact with the ground, must not transmit moisture from the soil to the grain.

The migration or redistribution of moisture is of concern in the storage of grains in bulks of 2,000 bu. or more (14, 28). Excessive accumulations of moisture occur in the central portions of the upper layer of the bulk. This takes place in the cooling-off period in the fall and early winter, when the inner portions of the stored grain are appreciably warmer than those next to the walls. Convection currents in the air surrounding the grain are created as a result of these differences in temperature. The warm air rising from the center of the grain mass is cooled in passing through the upper layer of grain, resulting in a moisture exchange from the air to the grain. The thickness of the layer affected is about 12 in. and its moisture content may increase to 30% in extreme cases. The accumulations are accelerated by heavy insect infestations since the insects migrate to the warmer portions of the grain where their activities raise the temperature and moisture content still further.

That it is an important function of the storage structure to protect grain from external moisture is obvious. The need for using methods that minimize or eliminate the migration of moisture is not so apparent.

This difficulty can be eliminated (28) in one or more of the following ways: (a) by storing grain in smaller bulks or at shallow depths; (b) by storing drier grain; and (c) by cooling grain during storage.

Storage structures have the important function of minimizing the large loss of grain caused annually by rodents and insects. Moreover, proper storage methods may be the only solution of the problem of meeting the requirements of food laws with respect to the presence of rodent hair and insect fragments in such products as flour. There is no problem in the storage of grain in structures which lend themselves readily to ratproofing. However, when corn is stored for a year or more in cribs, which are rarely ratproofed, the damage by rats is frequently excessive.

Although a grain bin is not considered to provide protection against the ingress of insects, it can be made to serve this function. Most infestations or reinfestations occur during storage (5). All joints of a grain storage can be made insect-tight, and all openings can be screened to keep out insects. Or the bin can be made air- or gastight (38), so that it is possible not only to keep out insects but also to exterminate those which may be present in the grain at the time it is placed in storage.

Temperature is an important factor in the storage of grain even when it is dry. Grain temperatures are influenced by microorganisms, enzymes, and insects, and by the ambient air temperature and solar heat. Excessive generation of heat within the grain is caused by microorganisms and enzymes only when the moisture content is above the safe storage limit. Insects may generate sufficient heat in local spots in stored dry grain to maintain a temperature as high as 105°F. (5, 39). This is true, however, only when the infestations are heavy.

In dry grain without heavy insect infestations, the temperature of the grain is influenced primarily by the ambient air temperature and the solar radiation. While the surface of grain and the layers next to the outside wall respond readily to a change in air temperature, there is a much greater lag in temperature changes in the grain farther from the surface or exposed wall (14). During the warmest part of the summer, solar heat can increase the average temperature of grain stored in galvanized steel bins as much as 10° to 12°F. over that stored in similar bins with walls and roof painted white, or provided with an equivalent reflective surface. Mechanical ventilation has been employed to keep high-moisture grain cool, thereby prolonging the storage period, and also to cool dry grain in cold weather in order to control insects and to minimize moisture migration. Although this development is recent, it appears very promising, so that it will probably be one of the accepted practices in the future, even in the larger storages (28).

Confining the grain in a bulk and protecting it against loss in quantity is a primary function of a grain storage structure. In addition to supporting the grain and resisting the lateral and vertical pressures, the structure should provide protection against loss by livestock, rodents, and theft.

Storage structures must be equipped for moving grain in and out of storage with convenience, and by mechanical methods in so far as practical. The more often grain is moved in and out of a storage, the better the facilities should be. Under usual farm conditions, where for the most part the grain is moved only once a year, the facilities need not be nearly as good as in elevators, in which large quantities of grain may be moved several times in a few months; that is, the appropriate type of handling equipment will depend upon the type and function of the storage structure.

In conventional types of grain storages, provision for periodic inspection of the grain is necessary for effective management (14). Although in farm-type storages samples may be taken through doors and small openings, a far more satisfactory method is to make samplings from above. Visual and physical inspections can also be made by crawling over the grain surface and inserting one's hand at arm's length at several locations. Fortunately, any heating or deterioration of the grain usually occurs first in the upper layers at or near the center of the bin. This often makes it possible to discover such changes readily by a surface inspection even without sampling equipment. Openings in the roof or walls which permit access to the top of the grain should therefore be provided. Sufficient headroom (4 to 5 ft. in the center area) for making an inspection of the entire grain surface and for obtaining samples with a grain probe is essential.

Often an inspection of the stored grain reveals that some form of conditioning or servicing is required to maintain quality. When heavy insect infestations are found, the standard practice is to fumigate without removing the grain from storage (14, 31). This is especially true of storages up to several thousand bushels in capacity. For successful fumigation, the floor and walls of the bin must be sufficiently tight to retain the fumigant gases. The tighter the walls and floor, the more effective the fumigation will be. If the grain contains excess moisture or if it is to be cooled in cold weather, the bin should be provided with ventilating ducts for this purpose. The storage structure should be equipped with doors and special openings to permit drying, cooling, and possibly the removal of troublesome portions of the grain.

Structural Requirements. The requirements for construction of grain storages differ from those of other buildings in that the floor and the

walls must be adequate to carry the weight of the stored grain. In addition, the walls must resist the outward pressures. The character and magnitude of the pressures vary with the grain and the type of structure, and must be carefully estimated to insure safe and economical design of storage structures. This subject has been widely studied and is discussed in detail in the next subsection. The following paragraphs deal with the structural requirements for foundations, floors, walls, roofs, and anchoring of grain bins and similar storage buildings.

The design requirements for foundations for grain bins are generally the same as for other buildings except for the heavier loads the bins must carry (26), which in most cases simply requires additional bearing area of the footing. The foundation in some cases may also be required to resist outward or lateral loads. Either additional footing area or ties are supplied to meet this requirement.

Floors of grain bins are of two principal types: those supported above the ground on piers, platforms, or foundation walls; and those placed on an earth, gravel, or cinder fill. The principal functions of a floor are to hold grain and fumigant gases, to provide protection from ground moisture, and to prevent entry of rodents.

The advantage of a floor supported 18 to 24 in. above the ground is the protection it affords against rats and ground moisture. Such floors also promote more rapid cooling of the stored grain. Concrete floors laid on fills should be at least 8 in. above the surrounding ground level. A construction with hollow masonry blocks and gravel as an underlay does not usually provide sufficient protection against ground moisture to avoid spoilage of grain next to the floor (36); for adequate protection a moisture barrier should be installed under the concrete floor (Fig. 1). Metal bin floors may be placed directly on a gravel or an earth fill. If all seams and joints are sealed, complete protection is provided against ground moisture. The underside of metal floors, even if zinc coated, should be given a coat of asphalt paint for added protection against corrosion. This type of floor should also be at least 8 in. above ground level.

Walls for grain bins must, in addition to meeting strength requirements, provide protection against rain water and hold fumigant gases. The preferred construction for frame walls is shown in Figure 1. It provides for two thicknesses of material on the outside of the studs, with a layer of waterproof paper between, and no lining on the inside of the studs. A second type of construction has a single layer of siding outside the studs with a layer of matched lumber, or any suitable building board, inside the studs. This type has the disadvantage of reduced storage capacity and allows the possibility of accumulation in the stud

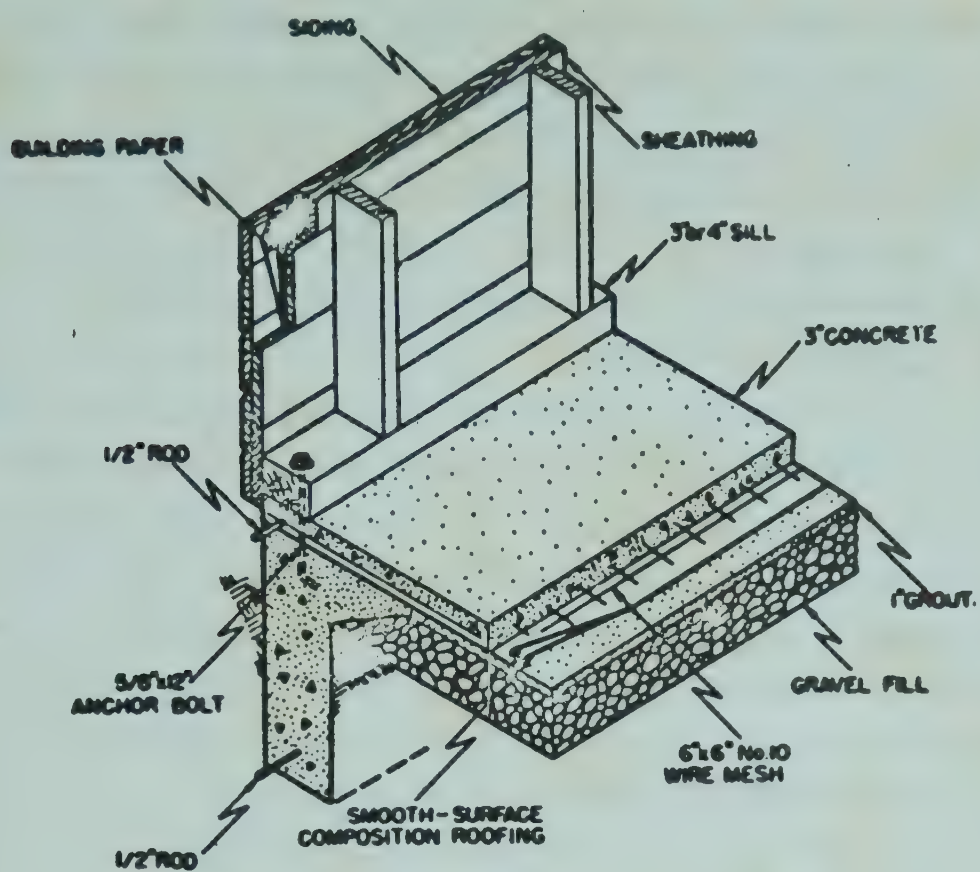

Fig. 1. Foundation, floor, and wall construction for wood grain bins. Note composition roofing for moisture barrier in concrete floor and building paper under siding for weather tightness (Shedd and Cotton, 31).

spaces of refuse that serves as a source for insect infestation. A single layer of siding, without any lining on the inside studs, while economical and used on a wide scale, is not raintight; it is unsatisfactory for this reason.

Bin walls constructed of hollow masonry blocks must be adequately waterproofed or lined on the inside to prevent leakage. The bolted wall joints of metal bins of the type commonly used on farms are usually sufficiently tight to serve under most conditions, but some calking may be required to overcome occasional leaks. Calked bins will also hold the fumigant gases better, and calking is a good precautionary measure to reduce the possibility of leakage to a minimum.

Thermal insulation in the walls of grain storages is not effective in preventing temperature changes in the mass of the grain, because the grain itself is a good insulator A 3-in. layer of wheat is equivalent to a 1-in. layer of a fiber insulation board (34). From the standpoint of keeping grain cool, or rather to keep it from warming up as much as possible, it is far more important to use a reflective surface or to shade the bin wall for protection against solar heat.

The usual standards of construction for roofs of buildings also apply to those of grain storages. Precautions must be taken to see that the roof is leakproof against driving rains and snow. In localities where snowstorms are prevalent, all joints between the roof and wall, roof

ventilators, and manhole covers must be virtually snowtight (24). The roof joints, including the junction between the roof and top of the wall, should also be tight enough to exclude insects. In this way a common method of infestation by flying and crawling stored-grain insects is prevented. Any openings in ventilators should be screened for the same reason. A tightly enclosed roof will also aid fumigation of the grain by reducing the escape of fumigants.

The roof and walls should be provided with a reflective surface to give protection from solar heat. The space under the roof should be ventilated, even when dry grain is in store, for the following reasons: (a) to dissipate the hot air produced by solar heat, and (b) to remove any moisture-laden air resulting from excessive moisture accumulations in the upper layer of grain during the cooling-off period. Any openings used for ventilating must be screened and must also be capable of being closed in localities where driving snow is a hazard.

The anchoring of smaller and less permanent grain storages against wind is necessary when they are empty. This is much more of a problem when the bins are installed on temporary foundations, especially when they are made of lightweight materials such as aluminum. Under normal circumstances, and with heavier and larger buildings, anchoring is hardly necessary. In this, as in other matters relating to the structural requirements for grain bins, standard building design and common sense provide the guiding principles.

Pressures on Bin Walls. Many studies (1, 8, 13, 16, 17, 22, 23, 25, 34) have been made over a period of years to evaluate the lateral and vertical pressures of grain on bin walls and floors and for the purpose of designing safer, more efficient, and more economical storage structures. Both analytical and experimental methods have been employed in the determination of these pressures. Two of the analytical solutions, Janssen's and Airy's, are briefly discussed and values are listed for the constants in their equations.

Janssen's (17) solution is based on the condition that the bin wall is rigid and supports some of the weight of the grain by virtue of the friction between the grain and the bin wall surface. In other words, some of the grain weight is supported by the wall and the rest by the floor. It is also assumed that the ratio (k) of the unit lateral to the unit vertical pressure is constant at all points within the stored grain.

The equation for the unit lateral pressure L (lb./ft.^{2}) on a vertical wall, which is given in detail by Ketchum (22), is as follows:

$$\text{Lateral pressure, } L = \frac{wR}{u'}\left(1 - e^{-ku'y/R}\right)$$

Where w = weight of grain (lb./ft.^{3})

u' = coefficient of friction of grain on the bin wall,
= $\tan \phi'$, where ϕ' is the angle of friction of the grain on the bin wall (deg.);
k = ratio of the unit lateral to the unit vertical pressure in the grain;
R = hydraulic radius, i.e., the area of the bin (ft.^{2}) divided by the circumference (ft.);
y = depth of grain (ft.).

Values for w, u', and k have been determined experimentally, for the principal small grains, by several investigators whose results are listed in Tables I and II. By inserting these values in the equation, the unit lateral pressures (L) can be calculated for bins of different dimensions containing various depths of grain. Moreover, the unit vertical pressure (V) can also be calculated since $k = L/V$.

The total outward pressure P on a section of wall of unit width, holding grain to a depth y, can be expressed as follows:

$$P = \int_0^y L\,dy.$$

The vertical load on this wall is u'P, the product of the coefficient of friction of the grain on the wall surface and the total outward pressure.

Janssen's solution is widely used in practice since it takes into account the principal factors which affect grain pressures. It is, therefore, applicable to a wide range of conditions encountered in design practice. Figure 2 gives the unit lateral pressures of shelled corn on the walls of a circular bin as determined by Janssen's formula.

In Airy's solution the grain is treated as a semifluid (1, 22). The load on the wall is considered to be due to a wedge of grain, between the wall and the plane of rupture, tending to slide down this plane. The total pressure P is opposed by the wall, and the combined frictional forces uR and u'P. The first of these is due to friction of the grain on grain at the plane of rupture, and the other to the friction of grain on the bin wall. Airy provides two solutions; one for shallow bins where the plane of rupture cuts the surface of the grain within the bin, and the other for deep bins where the plane of rupture cuts through the bin wall on the opposite side. These solutions, which are also given by Ketchum (22), are as follows:

$$L = wy \left[\frac{1}{\sqrt{u\,(u + u')} + \sqrt{1 + u^2}} \right]^2 \quad \text{for shallow bins,}$$

$$L = \frac{wd}{u + u'} \left[1 - \frac{\sqrt{1 + u^2}}{\sqrt{\frac{2h}{d}(u + u') + 1 - u.u'}} \right] \quad \text{for deep bins,}$$

where d = width of the bin (ft.);
u = coefficient of friction of grain on grain,
= tan ϕ, when ϕ is the angle of repose of grain
h = depth of grain (ft.)
w, y, and u′ are as given above.

As indicated by Tables I and II, many experiments have been conducted to establish the constants which enter into each of the solutions. Studies have been made in both small- and full-scale bins, and are described in detail in the references cited, some of which date back prior to the beginning of the present century.

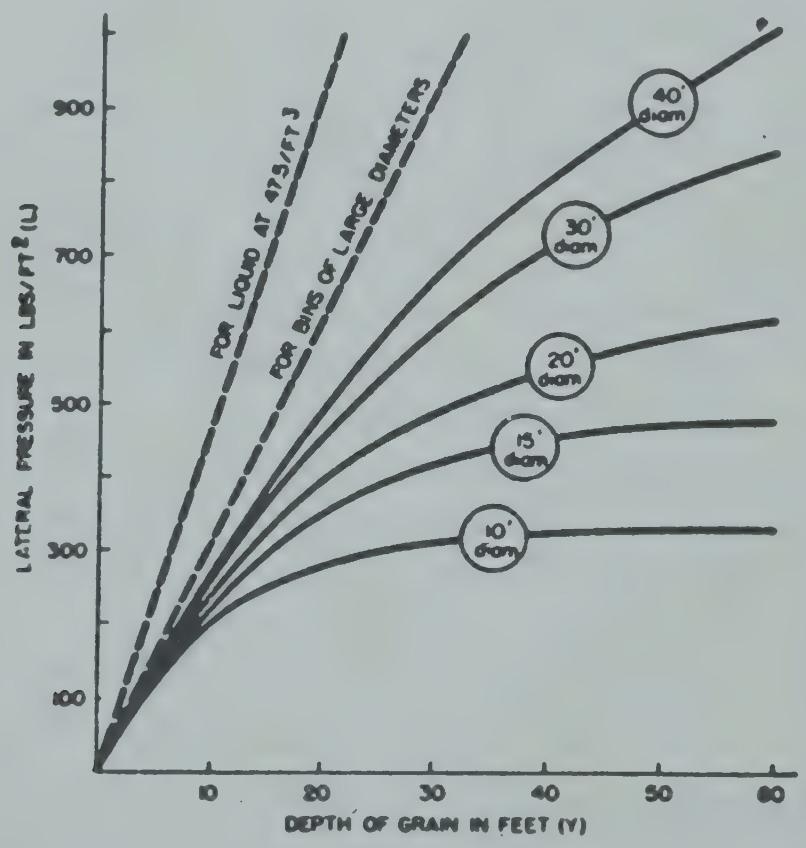

Fig. 2. Lateral pressures of shelled corn on walls of circular grain bins evaluated from Janssen's formula.

The conclusions regarding grain pressures are summarized by Ketchum (22) as follows:

1. The pressure of the grain on bin walls and bottoms follows the law of semifluids which is entirely different from the law governing the pressure of fluids.

2. The lateral pressure of the grain on bin walls is less than the vertical pressure, being 0.3 to 0.6 of the vertical pressure, and increases

very little after a depth of two and one-half to three times the width or diameter of the bin.

3. The ratio k, of the lateral to the vertical pressure which can be determined only by experiment, is not a constant but varies with different grains and bins.

TABLE I

BULK DENSITY (w), ANGLE OF REPOSE (ϕ), COEFFICIENT OF FRICTION (u), AND RATIO OF LATERAL TO VERTICAL PRESSURE (k)

Grain	Bulk Density (w)	Angle of Repose[a] (ϕ)	Coefficient of Friction of Grain on Grain ($u = \tan \phi$)	Ratio of Lateral to Vertical Pressure (k)	Authority	
	lb./ft.^{3}	*deg.*				
Barley	38.4	26.8	0.507		Airy	(1)
	40.0–43.2	16–28			Stahl	(35)
Corn (shelled)	44.0	27.5	.521		Airy	(1)
	47.0	27.0	.510	0.599	Caughey	(8)
	47.5	18.7	.34	.654[b]	Henderson	(13)
	48.0	16–27			Stahl	(35)
Flaxseed	44.8	24.3	.456		Airy	(1)
	43.2	14–25			Stahl	(35)
Grain sorghum	40.0–44.8				Stahl	(34)
	46.4	20–33			Stahl	(35)
Oats	25.6	28.0	.532		Airy	(1)
	33.6–35.2	18–32			Stahl	(35)
Peas	50.0	25.1	.472		Airy	(1)
Rice	36.0	34.0–36.0	.675–.727	.48	Kramer	(23)
		20–36			Stahl	(35)
Rye	44.8			.23–.45	Ketchum	(22)
	41.6	17–26			Stahl	(35)
Soybeans	46.0	30.0	.580	.383	Caughey	(8)
	46.4	16–29			Stahl	(35)
Wheat	48.0	24.9	.466	.30–.34	Ketchum	(22)
	46.0	27.0	0.510	0.612	Caughey	(8)
	48.8–52.0	16–28			Stahl	(35)

[a] Also referred to as the angle of friction of grain on grain.

[b] Determined from measurements in a steel bin 18 ft. in diameter with grain 11 ft. deep.

TABLE II

COEFFICIENTS OF FRICTION (u′) OF GRAINS ON BIN WALL SURFACES

Grain	Wood: Rough Boards	Wood: Smooth Boards	Wood: Cribbed Wall	Iron or Steel	Concrete	Authority
Barley	0.424	0.325		0.376	0.452	Airy (1)
	.554[a]			.479[g]		Stahl (35)
Beans	.435	.322		.366	.442	Airy (1)
Corn (shelled)	.344	.308		.374	.423	Airy (1)
	.302[a]			.447[g]		Stahl (35)
					.25	Caughey (8)
				.360		Henderson (13)
Flaxseed	.407	.308		.339	.414	Airy (1)
	.275			.372[g]		Stahl (35)
Oats	.450	.369		.412	.466	Airy (1)
	.380[a]			.445[g]		Stahl (35)
Peas	.287	.268		.263	.296	Airy (1)
Rice	.495—.542[a]	.435—.440[b]		.402—.449[c]	.473—.600	Kramer (23)
	.530[a]			.479[g]		Stahl (35)
Rye			0.54		.85	Ketchum (22)
			.78[d]			Ketchum (22)
			.37[e]			Ketchum (22)
			.55[f]			Ketchum (22)
	.330[a]			.406[g]		Stahl (35)
Soybeans					.27	Caughey (8)
	.312[a]			.368[g]		Stahl (35)
Wheat	.412	0.361		.414	.444	Airy (1)
			.43		.71	Ketchum (22)
			.58[d]			Ketchum (22)
			.25[e]			Ketchum (22)
			.45[f]			Ketchum (22)
			.420—0.450	.375—.400	.400—.425	Ketchum (22)
					0.35	Caughey (8)
	.277—0.298[a]			.340—0.366[g]		Stahl (35)

[a] Plywood across grain.
[b] Plywood with grain.
[c] Flat galvanized iron.
[d] Ringed cribbed bin.
[e] Small plank bin.
[f] Large plank bin.
[g] Smooth shiny tin.

4. The pressure of moving grain on the walls of the bins is slightly greater than that of stationary grain.

5. If a bin is emptied on one side, the lateral pressure on the wall opposite the opening is materially increased because of the movement of the grain from the bin. The lateral pressure is decreased on the side where the grain is discharged.

6. The maximum lateral pressures occur immediately after a bin is filled.

7. The pressures calculated by either Janssen's or Airy's formula agree very closely with actual pressures.

Bin Storage of Small Grains

The methods of storing small grains and shelled corn on farms and in the structures ordinarily used for the purpose vary rather widely with the climate and with moisture and insect hazards, and depending upon whether the storage is of a temporary or permanent nature. In selecting the type of structure (2, 31), attention must also be given to a number of other items including: kind of grain, season, market price, transportation facilities, and availability of materials and labor for erection. In the heavy wheat-producing areas of the Midwest, wheat is often piled on the ground for weeks until shipping facilities can be obtained for moving the grain to market. On the other hand, some farms have permanent structures with the most modern facilities for storing and conditioning grains.

Much of the surplus grain delivered in recent years to the United States government in liquidation of loans was stored in farm-type bins. However, larger buildings were also widely used. The longer storage period to which this grain was exposed, sometimes extending up to 5 years, and the storage of greater quantities in single bulks, focused attention on certain problems not fully recognized heretofore in either farm or elevator storage. During 12 years of experience and intensive field studies in connection with the storage of surplus wheat and shelled corn, the problems encountered have become well defined and some practical solutions have been developed.

In the following discussions both the grain bins and the larger buildings used for government grain are treated together. They present the same types of problems, though these are normally less apparent in smaller bins and over shorter storage periods. Types of storage structures and equipment for handling grain in and out of storage are discussed first. The principal problems encountered in keeping grain in condition are then considered. Finally, methods of conditioning grain are briefly described.

Types of Storage Structures. Figure 3 shows one of the simplest types of bins, commonly used by farmers in storing shelled corn or any kind of small grain. Ordinarily these can be made movable by mounting them on wood platforms provided with skids. The capacity varies from a few hundred to a thousand bushels. Such a structure provides satisfactory conditions for storing dry grain, but no provision is made for conditioning the grain in case storage difficulties develop. However, the grain can be easily fumigated and is less likely to be reinfested with insects than if it is kept in a larger granary containing more than one bin.

Fig. 3. A circular steel bin with a capacity of 1,000 bu. provides good storage for dry grain. This is readily made movable by setting the bin on a wood platform provided with skids.

In the Wheat Belt, structures with two or more bins are used for larger quantities of grain. These are usually arranged with a central drive and have an advantage over isolated bins in that the grain can be moved and some conditioning effected if the necessity should arise. On the larger grain-producing farms, specially constructed storages similar to small elevators are used. This type of structure requires careful planning. Many of the facilities found in the smaller elevators are used in such farm storages.

The practice of storing grain in barns, machinery sheds, and other farm buildings is very common, although the hazards of storage are greater. However, these buildings are used mainly for surplus grain and the storage periods are usually short. They afford good protection from the sun's heat, and grain placed in them in a cool condition is likely to keep quite well.

Fig. 4. Farm-type steel and wood bins used by the Commodity Credit Corporation for the storage of shelled corn and small grain (Holman, Barre, Cotton, and Walkden, 14).

Much of the surplus grain owned by the United States government was also stored in farm-type bins (Fig. 4). These were mostly prefabricated and ranged in capacity from 2,000 to 3,300 bu., which is about double the size of those commonly used on farms (4). The materials were mainly steel, wood, and aluminum, although other materials were used for a limited number of bins. These included plywood, insulation board, and cement asbestos board. The metal bins were preferable because of their economy and ease in shipping and erection.

Nearly all of the bins were erected with common labor. Moreover, they were erected on temporary foundations, which was considered to be contrary to good practice. But when properly done, satisfactory foundation support was provided for an indefinite number of years for both steel and wood bins.

To illustrate the versatility of this type of storage, in 1942 many thousands of steel bins in the Corn Belt were disassembled, trucked a distance of several hundred miles, and re-erected in the Wheat Belt for storing surplus wheat. Not only were materials conserved in a period when they were critical, but all of this was done at a cost substantially under that required for new storage.

In 1949, buildings of a conventional type were also procured for the storage of surplus grains. These structures are commonly referred to as "flat storages" and are also used in many localities by country elevators to provide additional storage. The widths range from 30 to 40 ft. and the wall height from 10 to 14 ft. A common length was about 100 ft. The storage capacities ranged from about 25,000 to 40,000 bu. Steel and aluminum were most commonly used in the construction. They were erected at selected bin sites on permanent concrete foundations. A moisture barrier in the form of reinforced, asphalt-impregnated paper was laid between the gravel or sand fill and the concrete floor slab.

Equipment for Handling Grain in and out of Storage. Portable elevators commonly used on the farm for handling small grains and shelled corn are quite simple. They are principally of two types, namely, the flight drag or chain type, and the screw conveyor or auger type (Fig. 5). The latter have the advantage of being simple, light, and easy to move from one bin to another. The capacities of the portable elevators vary somewhat. The larger flight-type elevator handles grain at about 2,000 bu. per hour, while an auger elevator 6 in. in diameter easily conveys 1,500 bu. per hour. Grain blowers are also used but to a much lesser extent. Although convenient, their principal disadvantage is the cracking of grain, especially when they are run at excessive speeds.

The use of portable elevators for handling grain in and out of storage in the larger government bins, and for turning and cleaning operations, was highly successful. Their portability and flexibility made it possible to adapt them to the widely varied field conditions. An important accessory was an auger-conveyor attachment about 12 ft. long, which was used to convey the grain to the elevator from points within a radius of about 12 ft. It was powered by the lower end of the elevator to which it was attached. This rather simple attachment was very effective and eliminated much hand labor in moving grain out of storage.

Fig. 5. A portable auger-type elevator which may be used for both loading and unloading grain from bins and trucks (Holman, Barre, Cotton, and Walkden, 14).

Principal Storage Problems. The more important problems encountered in the storage of grain in farm-type and similar bins include the following: (a) insect infestation, (b) wall and roof leaks, and (c) moisture migration. Insect problems are discussed in Chapter V and will not be referred to here. Difficulties encountered with leaks and moisture migration are discussed mainly in the light of experience gained in storing surplus government grain for periods of a year or longer.

One difficulty most commonly observed in every type of storage was the spoilage of some grain due to leaks (14). Even with extreme care in erection, and calking of all joints, some leaks still occurred. The bolted joints of wall and roof sheets in metal bins, as well as the single wall

construction in wood bins, are likely to develop an occasional leak in heavy driving rains. This was also common in the flat storages in which water from a serious leak would penetrate the full depth of the grain and cause spoilage of grain in contact with the floor. Careful construction and frequent inspection and repair are the only remedies for the difficulty.

Migration of moisture, from the warmer grain in the center of the bulk to that in the cooler surface layer directly above, has been observed in the fall in every type of storage (14, 15, 28). The increase in moisture content is sufficient to cause an appreciable amount of grain to deteriorate and under some conditions to spoil completely.

The redistribution of moisture in a 2,000-bu. steel bin of shelled corn is illustrated in Figure 6. During the fall the outer and top layers cool faster than the corn in the center of the bulk. For example, in November the temperatures of the corn in the center of the bin were 20°F. higher than those near the outside wall. These differences in temperature cause a circulation of air within the bulk of grain. Air next to the outside wall cools and settles to the floor and moves toward the center where it takes the place of the rising warmer air. As the warm column of air passes through the cool surface layer of grain in the center of the bin, some of its moisture is transferred to the grain by virtue of the greater water vapor pressure in the air as compared with that of the grain.

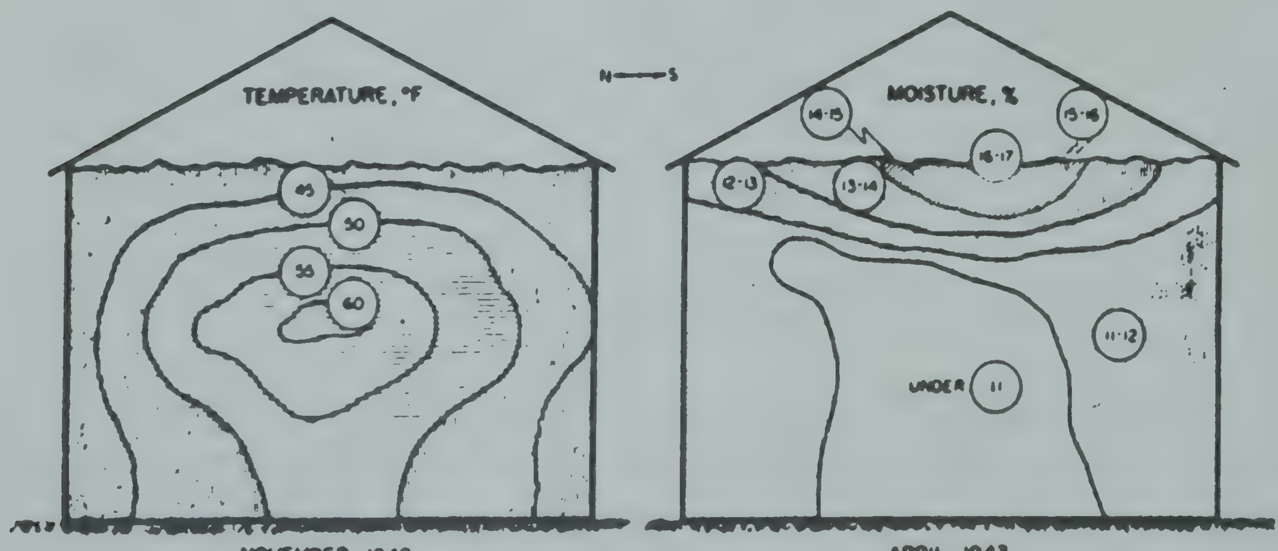

Fig. 6. Redistribution of moisture in a 2,000-bu. steel bin located in northern Iowa. The lower grain temperatures near the wall create convection currents within the bulk of grain, resulting in an accumulation of moisture in the upper layer in the center of the bin (Holman, Barre, Cotton, and Walkden, 14).

This transfer may increase the moisture content by 4 to 6% in the upper 10-in. layer of grain. The deeper the bin and the higher the average moisture content of the grain, the greater the accumulation will be. A heavy infestation of insects also produces a much heavier accumu-

lation due to the additional moisture and heat given off by the insects. Such moisture transfers often result in the spoilage of 5 to 20 bu. of grain in a 2,000-bu. bin.

Redistribution of moisture has also been observed repeatedly in flat storage buildings and in other large storages even with grains of relatively low moisture content (28). In these larger structures the moisture accumulations are usually greater and the corresponding damage resulting from such increases becomes more serious. In flat storages of 25,000-bu. capacity located in central Indiana, as much as 500 bu. of shelled corn in the upper 1½ ft. of the central portion of the grain bulk were severely damaged after the second year of storage. The average moisture content of the entire bulk of shelled corn was 13%. But at the end of the storage period the moisture content in the top 5-in. layer was 30%, and that in the layer 10 to 15 in. below the surface ranged from 14 to 20%. The corresponding amounts of damage in the two layers were 60% and 8.6%.

During the spring and summer when the temperature of the stored grain rises, the air circulation in the bin is reversed, because the grain next to the walls and in the top layer now becomes warmer than the grain in the center. However, the redistribution of moisture during this period is very small, resulting in only a slight moisture increase in the grain below the upper layers in the center of the stored bulk. The wet grain in the top layer dries out appreciably, but it will regain moisture during the cooling-off period in the following fall. Methods of eliminating excessive accumulations of moisture have been developed, and these will now be discussed.

Methods of Conditioning Grains. Grain is frequently harvested with a moisture content too high for safe storage without conditioning. Various conditioning methods are used, though some of them are ineffective and are responsible for much loss of grain every year.

The ranges in the moisture contents at which grains are commonly harvested in the Midwest are as follows:

Corn	14% to 25%
Wheat	9% to 17%
Oats	10% to 18%
Grain sorghum	10% to 20%
Soybeans	9% to 20%

The fall-harvested crops are usually much higher in moisture content than those harvested in the summer. Such late-maturing crops as corn and grain sorghum can seldom be harvested at a moisture content suffi-

ciently low for safe storage in unventilated bins. Ordinarily wheat and oats can be harvested dry enough for safe storage in bins, especially in the drier climates. However, in wet seasons and in humid areas, their moisture content is often excessive. The wide adoption of the combine in all areas has resulted in the harvesting of grains with higher moisture contents.

Certain preventive and control measures have been developed in order to condition grain or to remove the cause of a storage difficulty when it is discovered. The particular measure employed depends on the nature of the difficulty. Thus fumigation, often with prior cleaning of the grain, may be required to control insects (discussed in Chapter V). Among other conditioning methods, the most commonly used are as follows: (1) natural ventilation, (2) mechanical ventilation, (3) moving or turning, and (4) artificial drying. In farm-type bins both natural and mechanical ventilation have been used to cool and dry grain. Artificial drying in bins is being adopted to a limited extent. In larger farm storages and in elevators grain is cooled and mixed by moving or turning, and in elevators various forms of drying equipment are commonly used to dry grain with an excess of moisture.

Natural ventilation systems of various types have been employed to utilize natural air for cooling and drying. Figure 7 illustrates some of the common systems which have been most successful. Drawings (A) and (B) show ways in which ventilators are used in bins for natural ventilation, and drawings (C) and (D) show methods of installing ventilated floors or ducts, with fans, for mechanical ventilation of conventional bins.

The removal of moisture is accomplished in two ways, namely, (a) by diffusion of the moisture from the grain into the ventilator or through the ventilated wall, and (b) by movement of air through the grain. In general, the natural ventilation systems are ineffective for drying small grains that are high in moisture except when drying conditions are very favorable and strong winds prevail to force the air through the grain. They are capable of removing only about 1 to 2% of excess moisture (18).

The effectiveness of a natural ventilation system depends largely upon the degree to which wind forces can be utilized in moving air through the grain (20). The positive or pressure-type ventilator shown in Figure 7 (6) is more effective in utilizing wind pressures than the suction type. This difference results from the fact that the wind forces on the walls of a circular bin are mostly negative and thus tend to nullify the suction of the roof ventilator (10). Moreover, the pressure type utilizes nearly the full value of the maximum pressure exerted by the wind, whereas the suction type develops only 40% of the maximum pressure (20).

Mechanical ventilation of grain in storage has received wide accept-

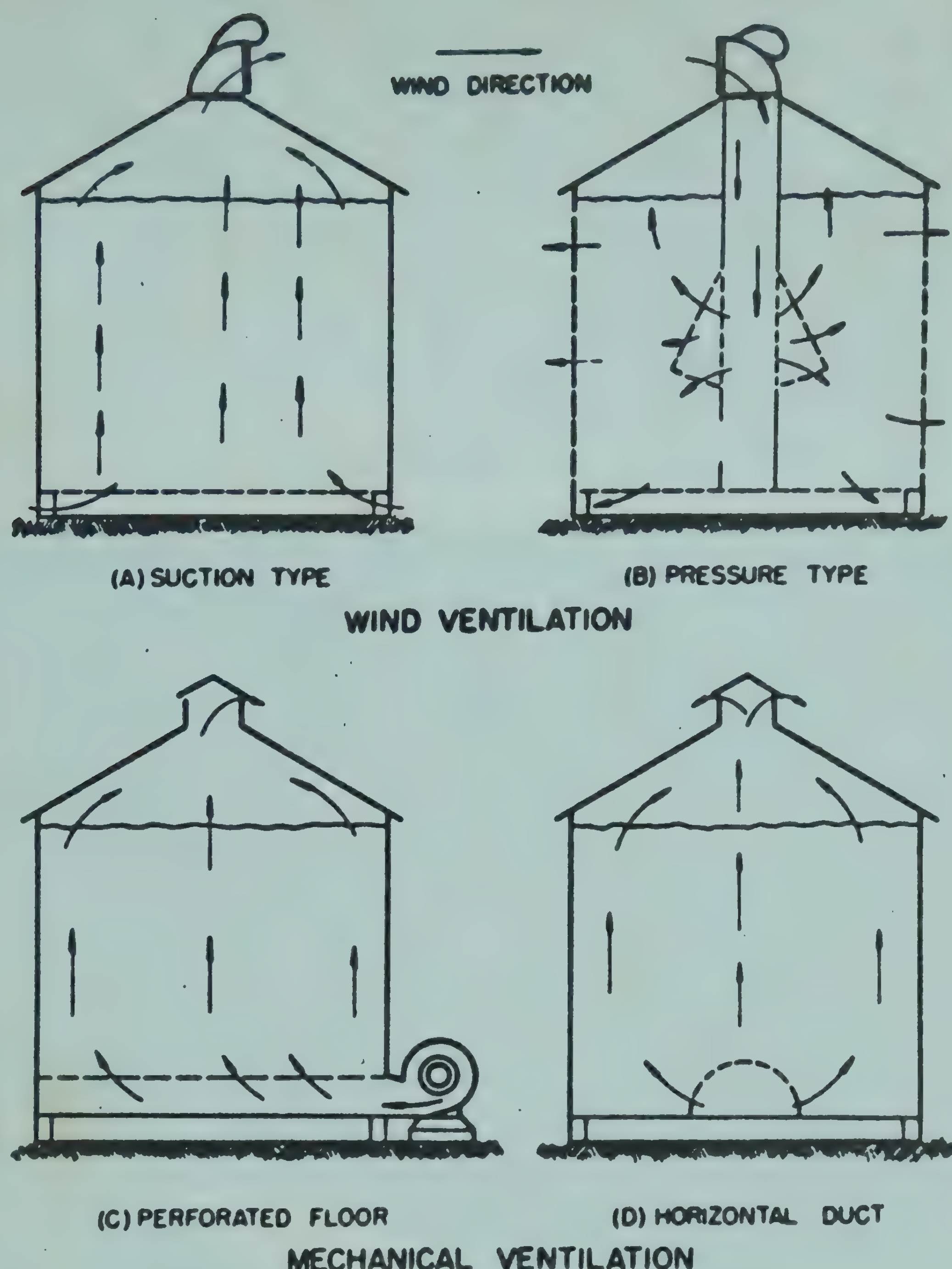

Fig. 7. Ventilation systems for grain storages: (A) the suction ventilator draws air through the perforated floor and up through the grain; (B) the pressure ventilator forces the air from a chamber in the center of the grain mass in all directions, the air escaping through the walls, floor, and surface of the grain bulk; (C) mechanical ventilation with a fan and perforated floor; (D) same as (C) except a horizontal duct replaces the perforated floor.

ance in the United States, not only on farms but also in larger storages and in elevators (11). In the larger storages, mechanical ventilation is used primarily for cooling the grain, although satisfactory drying has been demonstrated in flat-type storages containing as much as 25,000 bu. of shelled corn with 15% moisture (11, 28). However, several weeks of fan operation may be required to dry the grain, especially if its moisture content is high or if drying conditions are unfavorable. Even when no drying is accomplished, the grain can be kept cool by running the fan periodically. Or if portions of the grain are heating, the heat is soon dissipated and some drying is effected.

Mechanical ventilation has been used successfully to control moisture

migration by cooling the grain (28). This is particularly true in the "flat" type of storage. A horizontal duct (Fig. 8) which runs the full length of the building is simply placed on the floor. This may be a prefabricated type or one built up with two rows of concrete blocks covered with planks. The openings in the blocks and cracks between the planks are covered with hardware cloth or wire screen to keep out the grain. A fan powered by a 1½-horsepower electric motor is adequate to ventilate 25,000 to 40,000 bu. of grain. The fan is operated early in the fall and in the winter when the mean outside air temperature is at least 20°F. lower than the temperature of the grain.

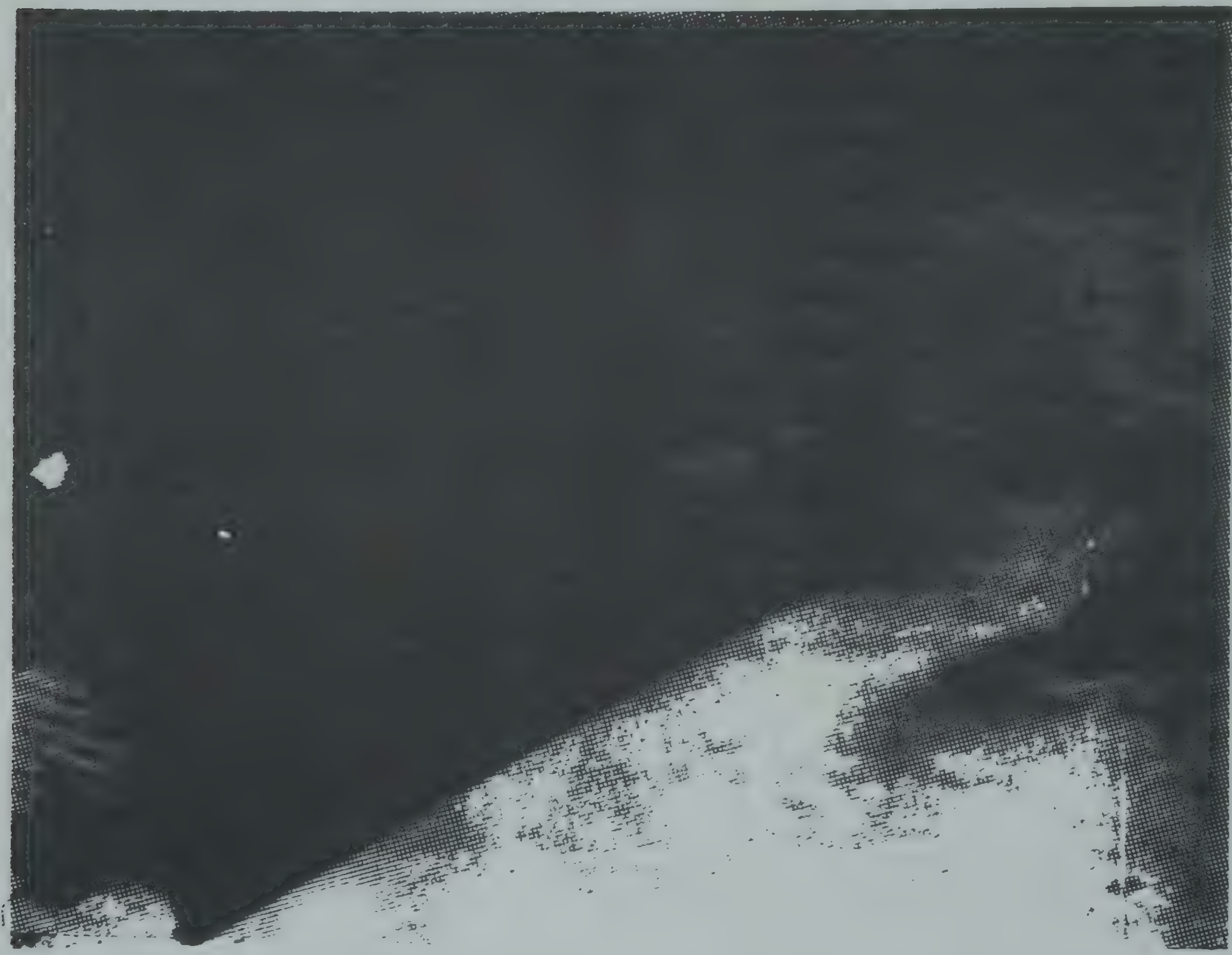

Fig. 8. A prefabricated horizontal duct of expanded metal developed primarily for cooling grain in flat storages. The duct is covered with a fine wire mesh or fly screen to make it grain-tight (Robinson, Hukill, and Foster, 28).

In an experiment in central Indiana the temperature of 25,000 bu. of shelled corn was reduced from 54° to 22°F. with 71 hours of ventilation. The mean air temperature during the period of cooling was 17°F. Air was supplied at a rate of about 0.25 c.f.m. per bu. The effectiveness of cooling became readily apparent on comparing the moisture content of the surface layers of grain in each of two storages, one ventilated and the other unventilated. The original moisture content was 12% in both cases. In December, after 14 months' storage without ventilation, the surface

layer of the grain in the unventilated storage contained more than 25% moisture, while that in the ventilated storage contained only 14 to 15%.

Effective cooling has also been obtained in tests made in Iowa with air flows of 0.1 c.f.m. per bu. The lower rates of air flow are just as effective except that a longer period of ventilation is required to accomplish the same amount of cooling. The air is drawn through the grain by exhausting it from the duct rather than forcing it into the duct and up through the grain. This has the advantage of cooling the upper layers of the grain first. At no point does the warmer air come in contact with cold grain which is the case when air is forced into the duct.

Moving or turning grain provides a further method of conditioning. Grain placed in a bin is rarely of uniform moisture content nor does any heating which may occur take place throughout the entire bin at the same time. By moving the grain from one bin to another, some cooling but no appreciable drying is accomplished. However, this method does mix the dry grain with the damper grain or the cool with the heated grain. This is often sufficient to maintain the grain in condition if repeated several times, especially when the excess moisture in the grain is only 1% or less. Although used widely in elevator storages, the procedure is not considered practical on farms, especially when the facilities for moving grain are not adequate.

Turning grain by moving it from one bin to another is commonly practiced in elevators when a storage difficulty is discovered. Even when no signs of spoilage appear, the grain may be moved at stated times, preferably in cold weather, as a preventive measure. Such an operation provides an opportunity to observe the condition of the grain in all parts of the stored bulk. Damaged grain may be removed and any faults in the storage building corrected.

In the conditioning of surplus grains owned by the federal government, the most common practice was to clean the grain as part of the turning operations. Much of the shelled corn and wheat so stored contained appreciable amounts of cracked grain and foreign material, which was more or less concentrated at one or more places in the grain bulk. Fumigation was relatively ineffective under such conditions, especially when the usual dosages were applied. Simple screens of hardware cloth 20 to 30 ft. in length were effective in reducing the amount of cracked grain and foreign material to less than a few tenths of one per cent. A portable elevator removed the grain from a bin and delivered it to the top of the cleaning screen. A second elevator received the cleaned grain from the cleaning screen and delivered it to a second bin.

Artificial drying is sometimes required in areas where conditions are too unfavorable for drying with natural air. The procedure involves

heating the air 10° to 20°F., to reduce its relative humidity to about 30%, and forcing it through the grain in the same manner as in mechanical ventilation. There is considerable danger of overdrying the grain next to the duct, and under certain conditions moisture may merely be transferred to the top layers of grain. This subject is discussed in Chapter IX.

Crib Storage of Ear Corn

Ear corn, which is often harvested in the United States Corn Belt with a moisture content over 20%, presents a different storage problem. The ears are stored in cribs which permit circulation of air to reduce the moisture content to a level at which the corn can be shelled and stored. Types of cribs, even within one locality, often differ in their construction, shape, and permanency. Since all cribs must provide for adequate ventilation, this matter is discussed first. The types of cribs in which corn is stored are then described, and further subsections deal with handling equipment and mechanical drying.

Crib Ventilation. The primary function of cribs used for storing ear corn is to reduce the large amount of moisture contained in the corn. For example, in the drying of a bushel of ear corn from an initial moisture content of 20% to a moisture content of 15%, nearly 8 lb. of water are removed. A free circulation of air is necessary in all parts of the crib to remove the excess moisture before the warm weather in the spring. Of course, the rate at which corn dries in a crib is limited by the humidity of the air and the temperature. Early in the fall, corn will dry rapidly. During the winter its moisture content falls to about 17–18%, or if already lower, rises to that level. Final drying takes place in the spring.

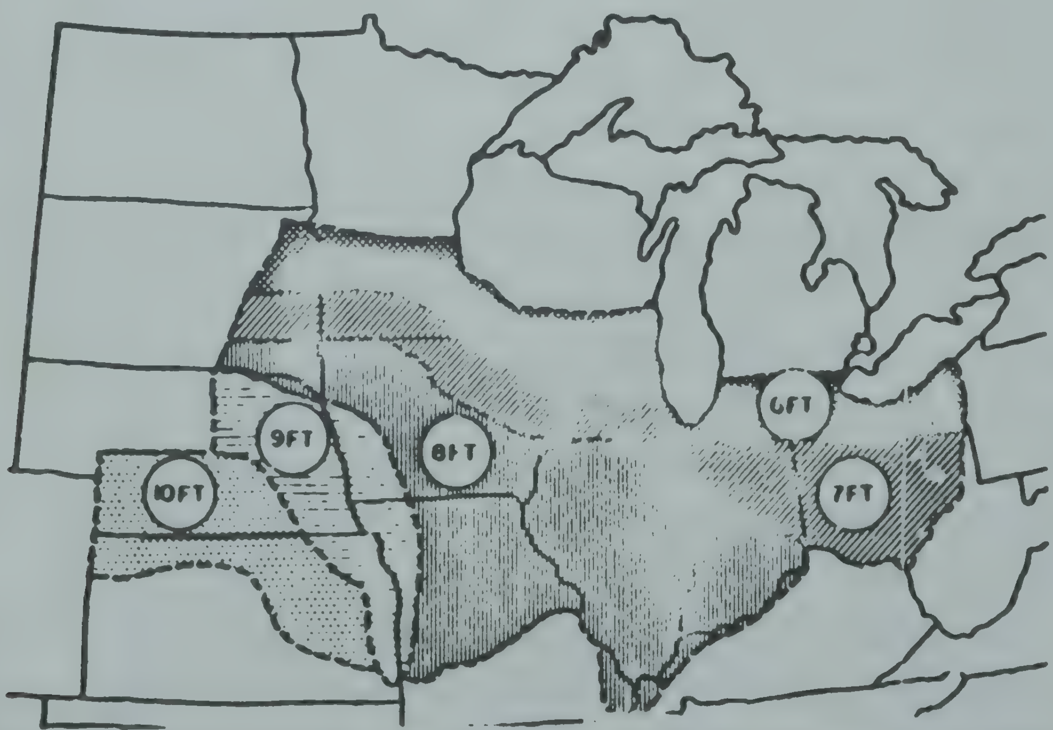

Fig. 9. Recommended maximum widths of rectangular cribs for storing ear corn in the commercial corn area (Shedd, 30).

The width of the crib is an important factor in determining the circulation of air. The narrower the crib, the more rapid the circulation because the wind is the primary motive force in moving air through the stored corn. Long experience has established maximum crib widths for different areas in the Corn Belt as shown by the map in Figure 9 (30). It will be noted that in the northern part of the Corn Belt narrower cribs are recommended. This is on account of the higher initial moisture content of the corn and the less favorable weather for drying. Round cribs, in general, are not as satisfactory for drying high-moisture corn as rectangular ones. If they exceed the width recommended for the area,

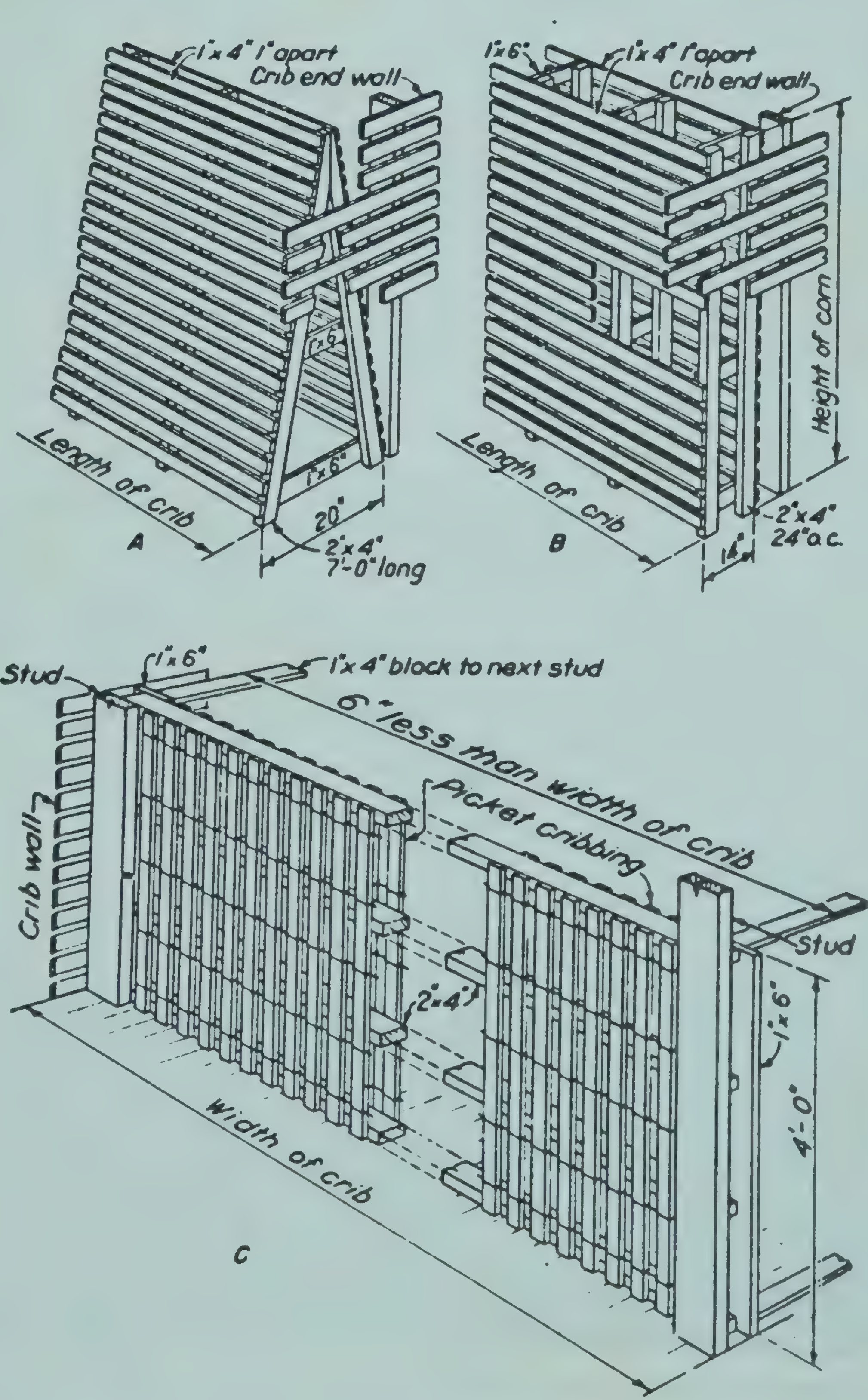

Fig. 10. Ventilators for rectangular cribs: A, A-frame, lengthwise; B, vertical, lengthwise; C, vertical, crosswise (Shedd, 30).

upright ventilators are placed in the center of the crib to aid the free circulation of air.

The walls of cribs are provided with varying areas of open space for ventilation. Although in practice the openings vary from less than 5% to nearly 100% of the gross wall surface, as long as the area is not less than about 10%, the flow of air will not be restricted. The resistance to air flow through a crib 8 ft. wide is almost entirely due to the corn and not the crib wall.

Experience has shown that to avoid the possibility of storage damage, ear corn should not be cribbed with a moisture content higher than 21% (30). If cribbed with a moisture content higher than this, additional ventilation of the type shown in Figure 10 should be installed in the cribs.

Types of Cribs. The types of cribs used in the Corn Belt may be classified by shape. For reasons apparent from the above discussion the type of material out of which the crib wall is made has little effect on the performance of the crib as long as the requirements for width and wall openings are met.

The rectangular crib is perhaps the most common type used, largely

Fig. 11. A single crib of a semipermanent type furnishes good storage for ear corn. It is well exposed to wind, has a good roof, and the floor is set above the ground (Shedd, 30).

because of its simplicity of construction and its effectiveness in the drying of ear corn. Figures 11 and 12 show common types of single and double cribs used throughout the commercial Corn Belt. The pole-type crib, while of a semipermanent nature, is commonly used to store the surplus part of the crop. Rectangular cribs may be built of different materials, although they are commonly constructed of wood. They are rarely of masonry construction because a large amount of steel reinforcement is required to resist the outward pressure.

Fig. 12. A common type of double crib with driveway. Both sides of the crib are filled from the roof hatch. Each side, which is 8 ft. wide and 36 ft. long, holds 1,000 bu. (Shedd, 30).

Round cribs of various types are very common and this especially applies to the temporary type of structure used for storing surplus corn for a short time. These temporary cribs are ordinarily made of snow fencing and are even used without roofs. Among the more permanent structures, many prefabricated types of cribs are circular in shape. Masonry construction is quite suitable for circular or oval structures. The construction is simplified and less reinforcing is required than in rectangular cribs. A common type is shown in Figure 13.

With facilities for mechanical drying, other types of buildings can readily be employed for the storage of ear corn. The added cost for mechanical ventilation is offset largely by more economical construction

Fig. 13. An oval double crib with driveway and overhead bins. The walls are constructed of concrete staves and reinforced with steel hoops (Shedd, 30).

due to the great economy effected by the use of a larger building. A building with unobstructed space, such as a machinery shed, can be adapted for ventilation by simply providing a central duct running the full length of the building. A fan is placed at one end of the duct, forcing the air from the duct through the corn. If the sides of the building are tight, they can be slatted on the inside to permit the escape of air. Grain bins with tight walls can also be adapted for storing ear corn with the aid of mechanical ventilation. Either a duct system is used or a ventilated floor is installed over the regular floor. Air is forced through the duct or ventilated floor up through the corn.

Equipment for Handling Ear Corn. Stationary and portable flight-type elevators are now commonly used in filling cribs. The stationary type is best adapted for use in cribs with a driveway and overhead bins (Fig. 14). Portable elevators are used with almost all other types of cribs. Not only can such elevators be moved from one crib to another but they have the additional advantage that they can be used for elevating small grains.

As an aid in obtaining a free distribution of air throughout the crib, the elevators should be provided with screens to remove shelled corn,

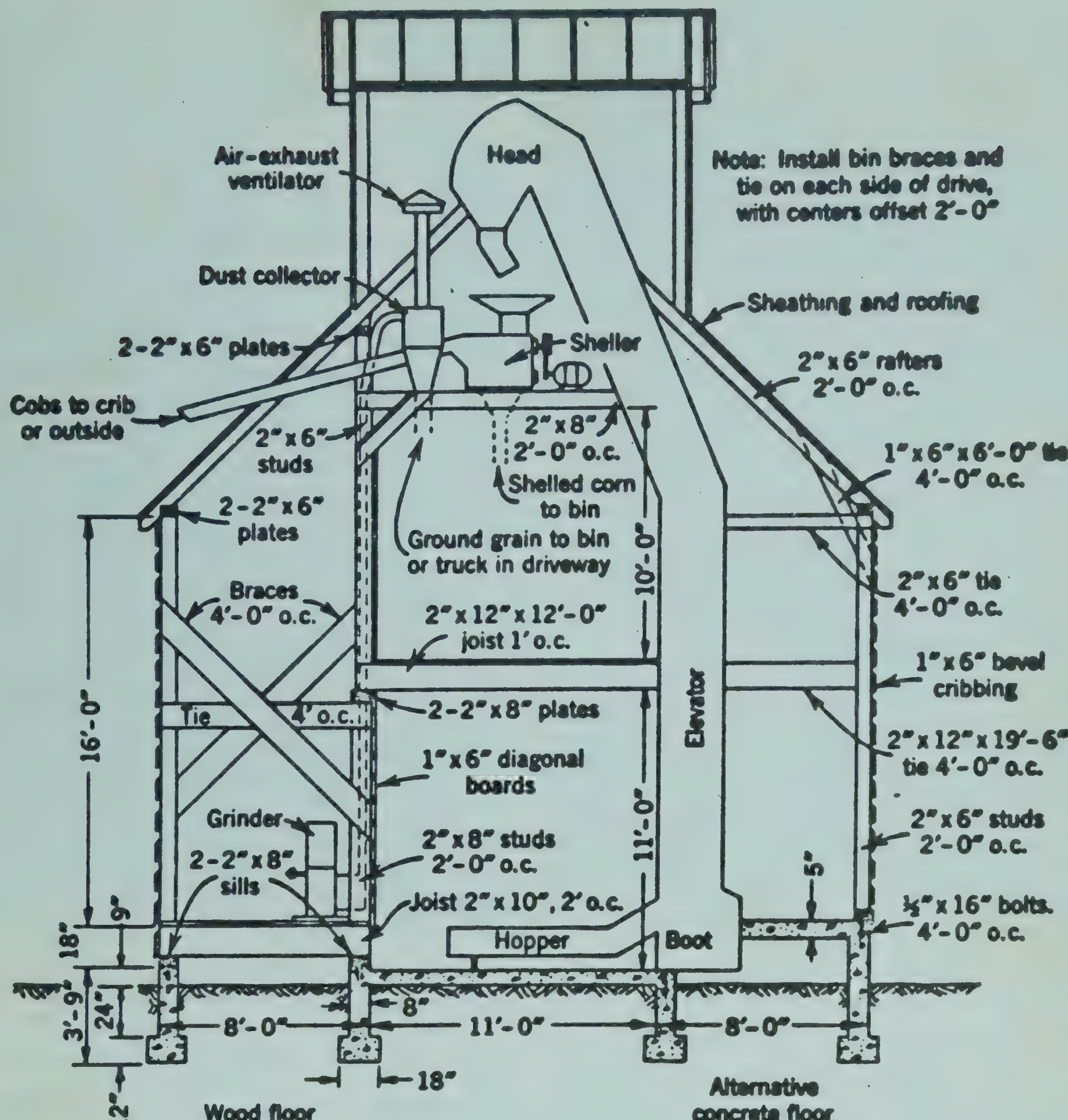

Fig. 14. Cross section of a combination crib and granary showing grain-handling equipment. A permanently installed elevator conveys all grains into storage. Ear corn is shelled in the area above the overhead bins. Grinding is performed in one of the cribs on the ground floor. Suitable methods of framing and cross bracing are also shown (Barre and Sammet, 6).

husks, and silks. Moreover, in filling the crib, the elevator spout should be moved frequently to distribute any of these materials that remain as widely as possible throughout the crib. Otherwise, a concentration of husks, silks, and shelled corn will result in poor air circulation and spoilage.

Shelling trenches are provided for ease in emptying cribs. Although more common in permanent buildings, they are also employed in the less permanent ones. Another way is to have a shelling door along one side of the crib. Portable conveyors can be used alongside the crib and corn permitted to empty into them for conveyance to a sheller or truck.

Mechanical Drying. Although this subject is covered specifically in another chapter, a few comments regarding its possibilities for conditioning ear corn may be noted. By means of mechanical drying, it is

possible to condition corn to a safe storage moisture content either in existing cribs or in buildings which are not otherwise adapted for ear corn storage. This method has particular application in conditioning ear corn which has a moisture content above 21%. It has been used widely in the drying of seed corn.

Mechanical drying can be accomplished with either heated or unheated air. The latter is used primarily for speeding up the drying of corn in existing cribs, especially when the moisture content is exceptionally high. The fan is operated on days when conditions are favorable for drying. This is ordinarily on clear days when the temperature of the air is above 50°F. The fan is operated until the moisture content of the corn is reduced to about 18%, after which natural ventilation of the crib is sufficient to bring the moisture down to a safe level.

By the use of heated air (Fig. 15) drying can be accomplished in a few days, provided sufficient air and heat are supplied to the corn. The corn is dried to a moisture content of 10–13%, at which point it can be stored safely in a tight bin, either in the form of ear or shelled corn. The air flow required is from 5 to 10 c.f.m. per bu. of corn. The temperature of the heated air should be limited to a maximum of 130°F. If the temperature is much higher than this, the quality of the corn may be impaired, especially if it is to be used for certain commercial purposes.

Country Elevator Storage

In the United States and Canada the country elevator is an essential element in the movement of large quantities of grain from producing areas to terminal elevator storage, processing plants, and grain deficit areas. The development of a wide system of country elevators throughout the Grain Belt has made possible the bulk transfer of grain in large volume. Country elevators are numerous and widely distributed over the major grain-producing regions; they are almost universally located with access to rail transportation. Over 1½ billion bushels of grain were received annually at country elevators in the United States during the period 1941–45. In 1945 they numbered about 16,500 (9).

The function of country elevators is concerned primarily with the storage, conditioning, and marketing of grain. Operations vary somewhat with location, the kinds of grain handled, and the extent of such processing operations as shelling, cleaning, and grinding of grains and mixing feeds. In the Wheat Belt the principal functions of a local elevator are to receive, store, and condition wheat, weigh it, and then load it into railroad cars for shipment to millers or to terminal and subterminal elevators. In the Corn Belt, particularly in heavy livestock-producing regions, only a part of the grain may be shipped out. In these areas there

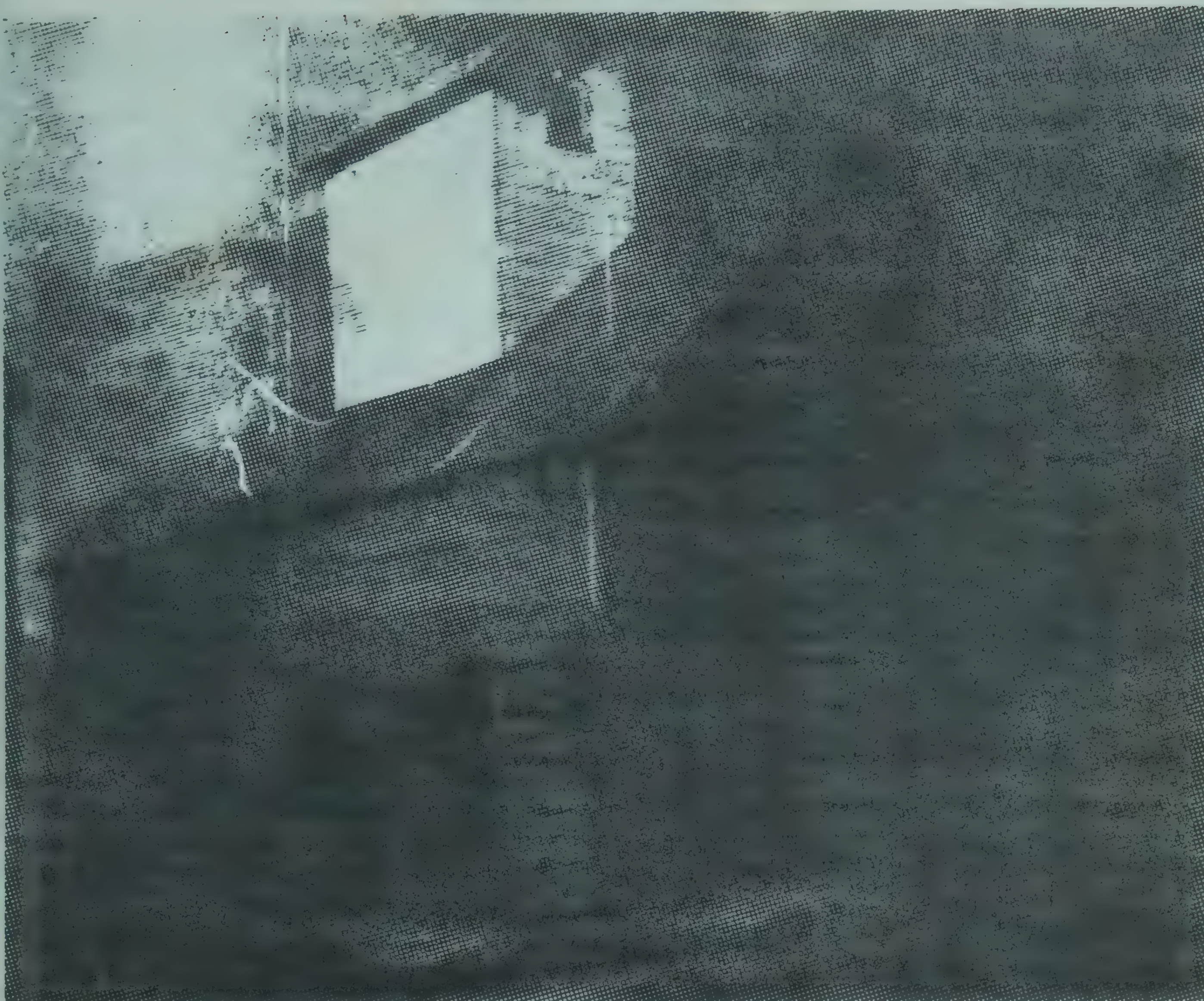

Fig. 15. Drying ear corn in one side of a double crib. A side duct of canvas is supplied along the driveway side of the crib and air is forced horizontally through the corn. (Courtesy of Rural Housing and Farm Structures Division, U.S.D.A.)

is a need for a convenient means of redistributing the locally produced grain for livestock feed; the elevator serves as a marketing center of grains and feeds for the community in which it is located. These elevators commonly offer such services as the grinding, mixing, and sacking of feeds for local consumption.

The usual capacity of country elevators is from 15,000 to 75,000 bu. The present trend is toward elevators of larger capacity; most of the more recently built elevators have storage capacities above 50,000 bu., and enlargement of older structures has been common. For the more common types of construction, the larger the capacity the lower is the cost per bushel of storage space.

Numerous studies of the economic phases of elevator operation have shown that the volume of business is an important consideration in determining the degree of financial success or failure of a country elevator enterprise. The volume of business measured in terms of bushels of grain handled per year should be several times the storage capacity of the elevator. Especially in the Corn Belt where there is more diversification in the types of grain produced, elevator storage is primarily short-term

storage. It is common practice to sell grain the same day it is purchased, thus minimizing the risk of loss as a consequence of market fluctuations.

In the Midwest there is a definite trend toward the larger combination processing, handling, and storage elevators; the number of small country elevators is being reduced. In Illinois the reduction has amounted to more than 25% in the past 10 years (27). Competition and improved methods of handling are largely responsible for this. Farm trucks and better highways, which make it possible to haul the grain greater distances, also contribute to this trend. Many of the small, less efficient elevators have depended entirely upon grain handling for income. They have encountered increasing difficulty in competing with the larger elevators which handle a greater volume of grain and usually derive substantial added profit from allied business or sidelines. These sidelines may consist of feed grinding and mixing, corn shelling, seed cleaning, trucking, and sales of manufactured feeds, coal, lumber, building materials, farm machinery, and petroleum products. Studies of grain elevator finances show that about 40% of the operating cost should be defrayed by sideline sales if an elevator handles less than 200,000 bu. of grain annually (7).

Country elevators may be classified into three groups with regard to ownership: (a) private elevators, (b) line elevators, and (c) cooperative elevators. Private elevators are owned by local individuals or firms and are more common in diversified farming areas. Line elevators are usually owned and operated by a large milling concern or a terminal market grain firm and are most commonly located in lines along the railroad systems in the wheat-producing areas. Organizations of grain producers own and operate the cooperative elevators and, as the name implies, the earnings of the elevator are prorated back to the producers on a share basis. Grain is handled in essentially the same manner in all elevators no matter how they are owned, the only difference being in the methods of financing and of distributing earnings.

Many elevators offer storage facilities for the use of grain producers at a charge of about 1½ cents per bushel per month, with additional charges for handling, insurance, and any conditioning that may be necessary during the storage period. Operators of country elevators often allow some free storage time or reduce storage charges on grain that is eventually sold to them. The storage of grain in public and private elevators is subject to many government regulations designed to protect the interests of both grain owners and elevator operators. Operators themselves do not usually wish to speculate on changes in grain market prices, and their business is conducted in such a manner as to eliminate most of the risk of loss due to market fluctuations. Accordingly, grain owned by the

elevator is stored for only short periods of time—often no more than sufficient for the assembly of carload lots of the desired quality for shipment to a terminal market or other point of delivery.

A detailed study of 27 grain elevators was made by Bruce *et al.* (7) in 1949, to determine their adequacy for the southeastern United States. This is an excellent reference to consult for further information on small grain elevators.

Fig. 16. A wood-type country elevator.

Types of Construction. Most of the older elevators are built of wood (Fig. 16). The storage bin walls consist of 2 by 6 in. or 2 by 8 in. planks laid on top of each other and nailed together in a manner known as crib construction. Although such elevators are relatively simple to build, the price of lumber and the large amount of labor required are serious disadvantages at the present time. In addition to high initial costs there are other disadvantages to the use of wood. Chief among these are the costs

of fire insurance. Fire insurance rates may vary from about $0.20 to $2.00 per $100 per annum depending largely upon the building materials used. The great difficulty of controlling insect infestation in wooden elevators is a further disadvantage.

As a consequence of these drawbacks there is a tendency to depart from wood and to use concrete or steel, and to a lesser extent tile, for the construction of country elevators. The adoption of improved methods of construction has helped to accelerate these changes. Thus the use of slip forms has simplified the construction of circular concrete bins, while the availability of prefabricated steel sections has facilitated the erection of bolted steel tanks with common labor. The current practice, then, is to build durable and fire-resistant elevators of reinforced concrete (Fig. 17) or steel (Fig. 18) by these more economical procedures.

Fig. 17. Country elevators of concrete construction. (Courtesy of Portland Cement Association.)

The cost of elevator storage space varies with the total capacity of the elevator and the geographic location. The minimum cost in the grain-producing areas is about $1.25 per bushel for elevators having capacities of about 75,000 bu. (27). This includes equipment necessary to elevate,

Fig. 18. A country elevator of bolted steel tank construction. (Courtesy of Butler Mfg. Co.)

clean, dry, and weigh grain. For smaller installations it is often more economical to use prefabricated steel instead of concrete.

Several factors must be taken into account when deciding upon the site for a country elevator. Usually access to rail transportation is still a matter of importance. In some areas, however, the trend is toward increasing use of truck transportation for shipping grain from the elevator, while improved highways have generally increased the area from which an elevator can draw its grain. Design of new elevators and equipment must now often be adapted to meet the wider use of truck transport.

The elevator site should be well drained and not subject to flooding. There should be ample space for parking and loading trucks and for later expansion of the plant. Adequate electrical service is important since many elevators use electric motors as large as 100 horsepower for such operations as grinding; and as the use of dryers is becoming common practice, an economical source of heat, such as natural gas, is an advantage.

The design and construction of an elevator require careful planning in order to insure that it will perform its particular functions with the greatest efficiency; it is usual to place this work under the supervision of an experienced elevator engineer. In elevators in the Midwest, labor costs constitute half, or more, of the total operating expense, and substantial

savings can therefore be effected by designing the plant and selecting the equipment with the object of reducing the labor required for their operation. Modern design and construction are aimed at reducing the necessity of a heavy labor load even during the peak harvesting season. Proper design in selection of materials and arrangement of the plant is also effective in reducing insurance costs, which are an important expense item.

Elevator Equipment. The equipment necessary for the efficient operation of a modern country elevator represents a substantial investment. Several of the items which are essential to every elevator are described in the following paragraphs.

Truck scales for weighing incoming loads of grain are usually located adjacent to the office building. Some have devices attached to the beam which record the weight on a scale ticket when the beam is balanced. Scales being installed at present are about 50 ft. long and are capable of weighing loads up to 50 tons with very good accuracy.

Trucks and wagons are unloaded by means of a hydraulic or mechanical truck lift which raises the front of the truck, causing the grain to flow out and drop into the receiving hopper. To prevent the entrance of larger objects into the hopper it is usually covered with a steel grating.

From one to three elevator legs are used in each elevator. Each consists of two pulleys, one at the top of the building and one in the basement, which carry a belt to which cups are fastened. The lowest part of the elevator, where the cups pick up the grain, is called the "boot"; the upper pulley with its discharge spout is called the "head." The belt is usually driven from the upper pulley by an electric motor. Elevator legs may be obtained in a wide range of capacities from 200 to 5,000 bu. per hour.

Distributor heads are used to deliver grain from elevator heads to bins, cleaner, dryer, or railroad car. The distributor spout is controlled by a vertical shaft which can be turned from the main floor, so that an operator at ground level can direct the flow of the grain through the elevator.

Cleaners of various types are used in elevators to remove foreign material from the grain. In those most commonly used, the grain is passed over wire screens or perforated metal sheets which usually have a reciprocating motion. A blast of air carries away dust, chaff, and other light impurities. Such cleaners can be obtained with capacities of 100 to 3,000 bu. per hour.

Cyclone dust collectors are commonly used to separate the dust from the air discharged from cleaners. These are fabricated from sheet metal in an inverted cone shape. The path of the air stream through the sep-

arators is such that the dust particles drop to the bottom of the collector by centrifugal action. Air is released through a vent in the top.

Bins in country elevators vary widely in number and capacity. The present trend is toward construction of circular bins of reinforced concrete or prefabricated steel with adjoining frame or crib construction for work space and to house equipment. Bins may have either flat or sloping bottoms; the extra expense of installing hopper bottoms is justified if the bins are to be emptied frequently. Grain being withdrawn from the storage bins moves by gravity flow, or by conveyor or belt, to the elevator leg.

Automatic dumping scales are usually employed for weighing grain that is to be shipped out. These automatically weigh from 5 to 10 bu. of grain and record each dump on a tally. They may be located in the headhouse so that grain flows by gravity to its assigned bin or to a railroad car on the track adjacent to the elevator; or they may be located on a lower level and discharge to an elevator leg.

Most elevators are designed to load out to railroad cars by gravity flow. A vertical drop of about 65 ft. is necessary to throw grain to the ends of a boxcar. Some elevators use car loaders which consist of a high-speed blower operated by a 10-horsepower electric motor. Trucks are loaded by gravity flow from a bin over the driveway or by means of truck-loading spouts from storage bins.

Some kind of "man-lift" is found in every elevator for moving workers rapidly from level to level. These vary in complexity from counterbalanced units for use by one man at a time to moving-belt types equipped with reversible steps.

Fire is an ever-present hazard in country elevators. Though such instances may be rare, two and sometimes three elevators built on the same site have been destroyed by fire, indicating the seriousness of the risk of loss, especially in older wood structures. Elevator owners now give careful attention to measures designed to prevent and control fires. Among these are the avoidance of dust accumulations and liberal placement of fire extinguishers throughout the building. Many elevators use overhead sprinkler systems.

Facilities for drying grain have become an essential part of modern elevators, especially in the more humid regions where grain is often received with a moisture content too high for safe storage. Even in less humid areas modern harvesting methods often result in receipt of grain with excess moisture; however, these methods are an advantage to both farmer and elevator operator in that damage and losses due to unfavorable harvest weather and to insects are largely avoided.

There are three general types of dryers in common use; namely, the

bin type, belt conveyor type, and the column type. In each of these systems heated air is forced through the grain. The temperature of the drying air is an important factor, affecting both the efficiency of the drying operation and the quality of the dried grain. The tendency is to use as high a temperature as is permissible since greater capacity can thus be obtained, and elevator dryers are commonly operated with air temperatures above 180°F. for drying grain to be used for feed purposes. But milling wheat, malting barley, seed grains, and grains for industrial use must generally be dried at lower temperatures if loss of quality is to be avoided.

The bin-type dryer is not commonly used in elevators; the floor area required is large, and this type of dryer does not lend itself well to mechanical handling of the grain. The belt-conveyor type is a fairly recent innovation and is not at present as widely used as the column type.

The vertical column-type dryer is in most general use. The grain is run into a holding compartment whose design may be one of several. The simplest consists of two pairs of vertical screens which, when filled, form two columns of grain. Warm air is blown between the upper parts of these two columns, which form two sides of a plenum, and moves out laterally through the grain; cold air, for cooling the grain, is blown between the lower parts. All column dryers have mechanical controls at the bottom so that grain can be held in them as long as desired, or released at various rates to a conveyor or elevator for return to a storage bin.

Elevator dryers, consisting of the grain compartment, heater, fan, grain-conveying equipment, and necessary controls, are commonly enclosed for weather protection in a separate building which is erected a few feet from the elevator building in order to meet fire insurance regulations. Heated air supplied by heaters of the direct type contains the products of combustion; this is not harmful and permits greater efficiency in the use of the fuels. Controls are provided to shut off the heater and fan in case of flame, ignition, or power failure.

Numerous other items of equipment may be employed in elevators depending upon the nature of the operations. Country elevators in the Corn Belt commonly receive corn in the ear and are often equipped with shellers having a capacity of 250 to 2,500 bu. per hour. These may be located in the basement adjacent to the dump pit or in the headhouse above the cleaner. Many elevators grind grain and mix feeds; grinders, mixers, bagging equipment, magnetic separators, hopper scales, and additional dust collectors are the usual items of equipment needed in the preparation of feeds for local distribution.

Grain temperature detector systems are finding increasingly wide use

in country elevators. These are especially valuable if grain is to be stored for comparatively long periods, since increases in temperature accompany many forms of grain deterioration. Cables or pipes, containing thermocouples placed at 5- to 6-ft. intervals, are suspended from the tops of the storage bins. The thermocouples are connected to a temperature-indicating instrument at some convenient location and the temperature at each thermocouple can be read as often as desired. Heating in any portion of the grain can thus be readily detected.

Elevator Operation. The operation of a country elevator varies in complexity depending upon the scope and diversification of the business. It may be relatively simple as in the case of the elevator which merely receives and ships grain. Ordinarily, however, there are other activities associated with this simple operation, such as blending, drying, and conditioning grain and storing grain owned by the elevator, farmers, mills, or government agencies. In addition, many elevators operate other services as important sidelines to their grain business. This discussion deals only with elevator operations pertaining to the handling and storage of grain.

Most elevators are operated in such manner as to provide a cash market for grain throughout the year. The amount of grain handled yearly is influenced by the size of the territory served by the elevator and by the importance of grain production in that territory. In the United States, 80 to 90% of the grain shipped out is normally marketed through country elevators.

Grain delivered at the elevator must be graded with some degree of accuracy. Samples for grading are either taken by probe at the time of weighing or obtained while the load is being dumped. Operators commonly make price adjustments on the basis of their measurements of moisture content, test weight, dockage, and damaged grain. Moisture testers which measure electrical resistance are widely used to give quick and reasonably accurate results. Test weights are determined by weighing a sample of grain of known volume, while dockage is determined by weighing the amount of fine material in the grain which will pass a standard sieve. Percent of damage is obtained by inspection for moldy, discolored, heated, sprouted, and otherwise damaged kernels. Ordinarily only those tests are made which are required to establish the price of the grain. Much grain is purchased by experienced operators of country elevators on the basis of visual inspection only.

On arrival at the elevator, the truck or wagon with its load is weighed and then the grain is emptied into the dump hopper from which it is moved into the elevator by gravity or by conveyor. From the elevator head the grain flows to the distributor which is set in proper position to

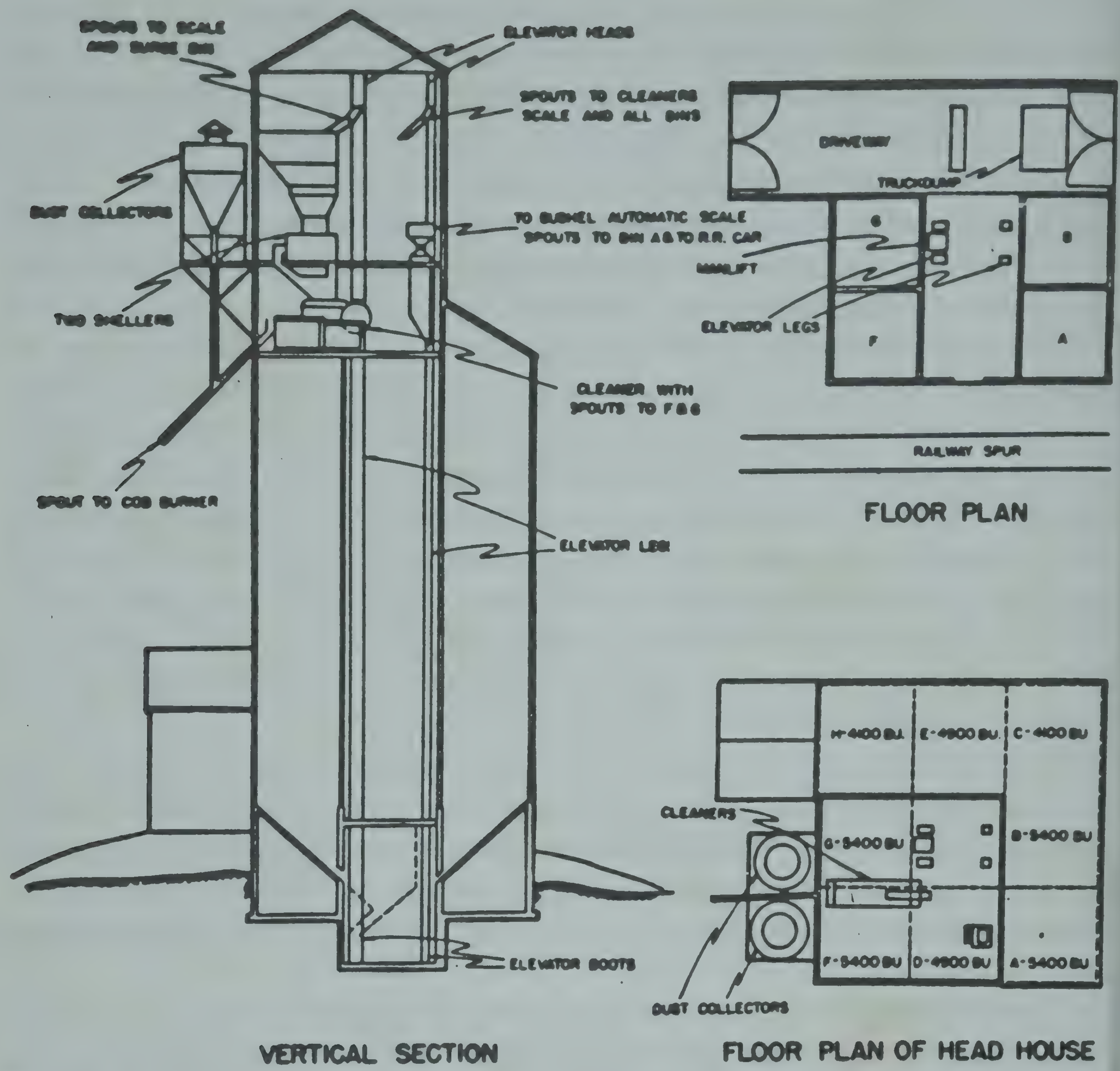

Fig. 19. Vertical section and floor plans of a typical country elevator of wood construction showing grain handling, corn shelling, grain cleaning, and weighing equipment. (Taken from plans by the Harry E. Surface Co., Kansas City, Mo.)

spout it to the desired bin or to cleaner, dryer, or railroad car.

Figure 19 illustrates the arrangement of a typical country elevator of wood crib construction which has a storage capacity of nearly 40,000 bu. of shelled corn or small grain. The principal parts of this elevator include several large storage bins, the grain dumps, and the headhouse. As is usual with this type of wood construction, the building and the individual bins are rectangular in shape and the outside walls of the entire structure are clad with galvanized sheet metal for weather protection.

The elevator illustrated has hopper bottoms in all bins, permitting them to be emptied readily. Elevators often receive grain with a moisture content that is too high for safe storage and it is common practice to

move or turn the grain frequently to maintain it in condition. This operation is especially prevalent when drying equipment is not available. Hoppered bins which can be completely emptied without shoveling are then a great advantage.

The extent to which grains are cleaned and blended prior to shipment from country elevators varies widely according to the facilities in the elevator and current conditions. In many elevators the principal use of the cleaner is to clean corn coming from the sheller, other grains generally being shipped without cleaning. The official grades of outgoing shipments can often be improved by judicious mixing of the grain in storage. For example, if the grain standards allow 5% damage for a given grade of shelled corn, a quantity of corn having 10% damage may be blended with a larger amount containing less than 5% of damaged kernels. Again, since the grading system provides no premium for grain having a moisture content below a specified level (14% for wheat in the United States), receipts of higher-moisture grain may often be blended with dry grain so that the mixture approaches but does not exceed the maximum moisture content carrying no discount.

When grain is stored for considerable periods of time, the operator must be familiar with the various forms of deterioration that may occur and the effective preventive measures. The common method of maintaining grain condition is to "turn" it, i.e., to move it from one bin to another. The greatest benefit of this procedure comes from the dispersion of localized trouble spots in the grain mass and the cooling of the grain under winter conditions.

In the United States country elevators normally sell 60 to 70% of the grain they handle to terminal markets (37). Most of the remainder goes to millers, corn refiners, cereal manufacturers, and feed manufacturers, and directly to feeders in the form of mixed feeds. In some areas considerable quantities of grain are shipped by trucks to nearby destinations, but the bulk of it goes to terminal markets by rail in freight cars which now have a capacity of 40 to 50 tons. To find the most favorable markets and the best means of shipment are important aspects of country elevator operation.

Special Types of Storages

Gastight Storage. Gastight or hermetic storage is defined by Vayssière (38) as "the storage of an agricultural product within a container in such a way that the product is protected from any exchange of gases or liquids with the outside environment." According to the same author its advantages are as follows:

1. It causes the destruction of insects and other pests present in the

grain at the time of storage.

2. It prevents the admittance of insects and other pests during storage.

3. It prevents mold development and heating in products carrying excess moisture though without stopping the development of acidity resulting from anaerobic fermentation.

4. Products that are dry at the time they are stored remain dry since they cannot take up moisture from the atmosphere.

In gastight storage insects are exterminated as a result of the oxygen depletion and the increased carbon dioxide concentration brought about by the respiration of insects as well as of the grain. Experiments have shown that either the depletion of oxygen or the increase in carbon dioxide will destroy insects in a period of hours or days, depending on oxygen and carbon dioxide concentrations, the species of insect, and on such factors as the temperature and moisture content of the grain.

Although some of the facilities used in foreign countries have been referred to as either sealed or hermetic storages, it is doubtful whether the conditions of hermetic storage are completely realized. However, as may be noted in the discussion of underground storage which follows, these conditions may be satisfied sufficiently to hinder development of insects even though they may not be completely exterminated. This is true not only of contemporary storages but also of those used in the past (38). To obtain true hermetic conditions the container must be made of sheet metal with all joints welded or soldered. The storage unit must be so constructed that it can finally be closed with one or more hermetic closing devices of the type used for vacuum appliances.

A modern gastight storage developed by the A. O. Smith Corporation of Milwaukee, Wisconsin, for the storage of forages appears to offer some advantages in the storage of grains of high-moisture content. It meets all of the requirements set forth by Vayssière (38) for hermetic storage. Briefly, the construction consists of a heavy concrete foundation and floor, with walls and roof of steel plates which are bolted and adequately sealed at all joints and connections. To maintain a gas pressure within the silo equal to that of the atmosphere, an impervious bag positioned in the space between the roof and grain surface is connected to the outside air through an opening in the roof. The bag inflates and deflates with changes in pressure in the atmosphere or that of the gas in the silo without permitting outside air to come in contact with the grain. However, the bag is not designed to accommodate all extremes in pressure changes. A special relief valve is provided at the top of the silo to admit outside air or allow the escape of gas from the silo whenever the predetermined negative or positive pressure is exceeded. The oxygen admitted with the entrance of air through the valve is not detrimental,

since the amount is relatively small and is soon consumed by the grain. With the pressure equalized at all times, the effect of any possible leaks is minimized. Moreover, the amount of air which may enter the silo while grain is removed through a grain door at the bottom of the silo is also kept to a minimum.

Storage experiments with high-moisture shelled corn in these silos have been conducted at the Indiana Station during the past several years. The results show that the grain does not heat and insects do not develop. The principal changes noted in shelled corn with excess moisture after several months of storage were a sour or fermented odor, complete loss of germination, and an increase in fat acidity. The rate at which these changes take place depends on the moisture content and the temperature of the grain.

Underground Storage. Underground storage of grain has been practiced extensively in a few foreign countries. The principal advantage claimed for the method is that it gives complete control of insects by maintaining an oxygen-free atmosphere around the stored grain. The temperature of the grain may also be kept down by the cool earth. Protection against ground and surface water is essential. Even if the soil seems dry, the floor and walls may impart sufficient moisture to the grain to cause deterioration unless they are covered and adequately moisture-proofed.

Storing grain underground is practiced on the island of Malta with apparent success (21). The bins are about 15 ft. in diameter and 25 ft. deep. As airtight a condition as possible is maintained to restrict the insect activity, and before the bins are filled their walls and floors are covered with layers of straw to provide protection from dampness.

In Egypt a common practice in the rainless region is to store grain underground in ditches covered with sand (3). If sufficiently dry the grain keeps well and remains free from insect infestation. Near the Nile Delta, grain has been stored successfully in pits with dome-shaped roofs, and with floors and sides plastered with mud and lined with straw. The pits are 3 meters deep and 2 meters in diameter. Insects do not multiply in grain stored in these pits. Before removal of the grain, the pits are aerated for the safety of the workers.

Recent experiments and experiences with underground silos for the storage of grains in Argentina and Paraguay are reported by Gattoni (12). The results are so encouraging as to give rise to the hope that this method may be used to preserve surplus grain through years of plenty. In such silos grain can be safely stored for 3 years or more. Even if the grain is heavily infested when it goes into storage, the insects are destroyed without injuring the germination and other qualities of the grain.

These underground silos can be constructed cheaply in Argentina and Paraguay. They are very similar to the deep trench silos used in this country for silage. However, the walls are carefully shaped to a slope and floors and walls are lined with either plastered brick or a monolithic concrete consisting of a mixture of soil, sand, and about 10% Portland cement. In either case a waterproofing material is applied. The bins are filled flush with the top of the wall which extends only a short distance above ground level. A covering of one or more layers of waterproof paper is applied and carefully sealed at the joints and at the junctions with the top of the wall. Figure 20 shows one of these silos; Figure 21 gives some of the details of construction and the principal dimensions of a typical example. In Paraguay permanent roofs are placed over the silos to provide added protection against the heavier rainfall and the higher temperatures. The capacities of these silos range from 160 to 580 metric tons of grain. In 1948, a total of 1,540 of the larger size were built in Argentina, and in the following year 10 of the smaller size were built in Paraguay.

With improved methods of construction and waterproofing, the loss of grain is reduced to 0.5%. A satisfactory waterproof covering for the

Fig. 20. One of several underground silos constructed in 1949 in Paraguay for the storage of shelled corn. The surface of the grain when the silo is filled is only slightly above the ground surface and is covered with waterproof paper (Gattoni, 12).

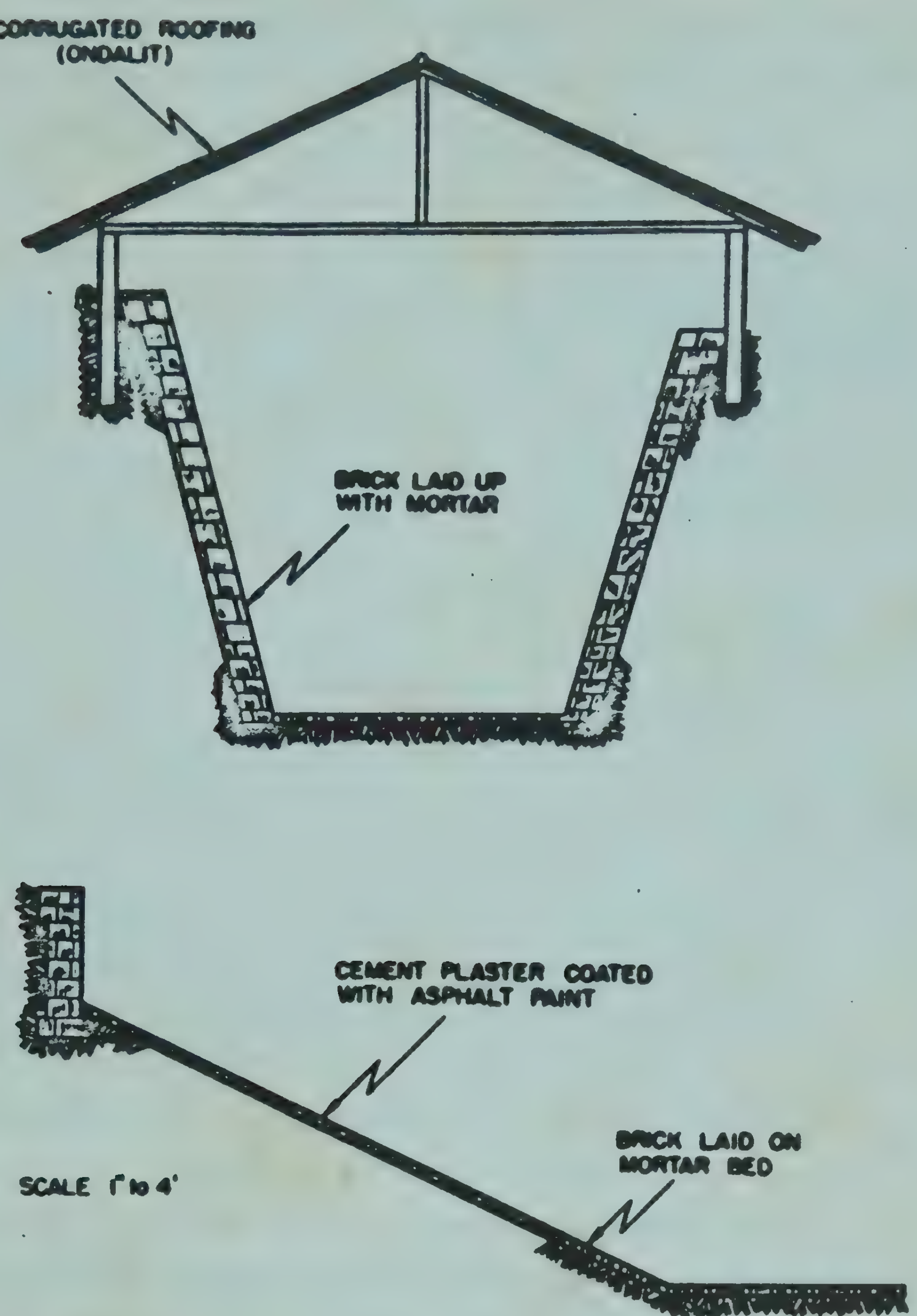

Fig. 21. Cross and longitudinal sections of a 400 metric ton silo showing its construction features. The surface of the grain when the silo is filled conforms to the slope of the end walls to drain off any water which may collect there (Gattoni, 12).

surface of the grain and a good method of waterproofing the walls and floor are the keys to the successful use of these underground silos. Such wall-covering materials as straw, reed mats, cardboard, and canvas were tried, but in some cases as much as 10% of the grain adhered to the wall on account of dampness.

All grain above a moisture content of 12% was dried with artificial heat to this level before it was stored in the silos. In the opinion of the present author, however, grain carrying as much as 16% moisture could be stored successfully, judging from the performance of these storages in maintaining high carbon dioxide concentrations which completely controlled the insects.

Studies were conducted prior to 1940 by the U.S. Department of Agriculture (21) to determine the advantages of storing wheat in pits. Some research has also been conducted in South Australia (33) to de-

termine the effectiveness of underground storage for insect control. The references should be consulted for details of these experiments. At Hays, Kansas, and at Urbana, Illinois (21), the greatest hazards found were the accumulation of moisture near the bin walls and the length of time required for the grain to cool after it was placed in storage. Some auxiliary method of cooling the grain was required in order to take full advantage of the lower ground temperatures. Different ways were tried to protect the grain against ground moisture. A layer of straw on the walls and floor as used in Maltese bins proved to be unsatisfactory. However, an aluminum foil paper formed an effective moisture barrier, and a fly screen formed about 3 in. from the plastered wall also appeared to give adequate protection. In the latter case, the space between wall and screen can be utilized in cooling the grain. If wheat is sufficiently cooled and adequately protected against moisture, it can be stored in pits with less deterioration and for longer periods than in conventional storage.

*Temporary Storage in Piles.** Nearly every year, large quantities of wheat and grain sorghum are temporarily stored in piles on the ground (Fig. 22) in Kansas, Oklahoma, and Texas because of the lack of trucks or boxcars. Some of the better growers use this practice to cool and condition the grain before placing it in their permanent storage, while some adopt it as a matter of convenience and economy. Farmers can market their grain in a more leisurely fashion after the rush of harvest is over and thus avoid heavy trucking charges prevailing during the harvesting season.

The success of the practice of piling grain on the ground depends upon the following factors: (1) the weather during the period of exposure; (2) the ground upon which the grain is piled and the drainage at the edges of the piles; (3) the care exercised in piling the grain; and (4) the length of time the grain is exposed. Many growers believe that they suffer no loss whatsoever by the practice of piling wheat on the ground for a period of 2 weeks to 2 months, and for the most part no losses in quality are suffered. In some years and in some individual cases, however, the losses are quite large.

When rain falls on a pile of wheat, only the top ½ in. is wetted. The sloping surface of the pile, like the roof of a building, sheds the water; and this happens even under heavy rains, up to a rate of 4 in. per hour, when the runoff may carry kernels down the sloping surface. If the rains are temporary and followed by sunshine and drying winds, the pile dries very quickly without apparent damage other than a bleaching of the

*Information supplied by Professor F. C. Fenton, Head of Agricultural Engineering at Kansas State College.

Fig. 22. Temporary storage of wheat in piles in western Kansas. (Courtesy of Prof. F. C. Fenton, Kansas State College.)

grain in the surface layer.

Buffalo grass sod is preferred as a floor for a grain pile, but any well-drained site will serve. The critical point is the lower edge of the pile where a large amount of water must be disposed of. If drainage is not good at this point, water will run back under the wheat and wet large quantities near the ground. Many piles have been observed in which the lower 8 in. of the pile was a mass of sour, moldy grain. The practice of laying waterproof paper on the ground may do more harm than good, for the paper is likely to be turned up at the edges, forming dams which direct any runoff water under the pile where it has no chance to drain away or to be absorbed by the ground. If a rainy period extending over several days is experienced, unbroken by drying weather, the grain on the surface of the pile will sprout, causing a heavy loss. The practice of piling grain on the ground should therefore be restricted to normally dry areas.

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CHAPTER VIII

Terminal Elevator Storage

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A terminal elevator is a device for the storage and handling of large quantities of cereal grains. It is called an elevator because grain is elevated to the top of the building before it is poured into storage bins. When grain is removed from the bins it is again elevated to the top of the structure, whence it is poured into boxcars, trucks, or vessels.

Terminal elevators are usually located in terminal markets, at large rail centers, or at points of transfer from one method of transportation to another. Terminal elevator storage capacities tend to accumulate in the path of the flow of grain from large producing areas to large consuming areas. For that reason they are found predominantly to the east of the Great Plains areas in the United States and Canada, and at the export and import harbors.

The prime function of a terminal elevator is the storage of cereal grain between its production and consumption. A typical elevator consequently consists principally of a group of gigantic bins towering high in the air (Fig. 1). Each bin may be large enough to store the annual produce of 100 farms, and to keep it safely through the months between harvest and the time it is sold to processors.

In addition to serving as warehouses for grain, however, terminal elevators have a number of other economic functions, or methods of being of service. These may be divided roughly into two groups, one group having to do with improving quality and the other with serving the marketing processes.

Quality may be improved in many ways. Grain received by a terminal may be dried, cleaned, washed, separated, or sized in order to make it more attractive to the processor. Various grades and qualities may be collected, sorted, and blended. Large lots of uniform quality to meet specific processing needs may be accumulated. Insect infestations may be controlled, incipient heating or spoilage arrested, and lots that cannot be stored safely may be moved toward immediate consumption.

The services a terminal elevator can render to the marketing processes

Fig. 1. A large terminal elevator at Port Arthur on the Great Lakes.

are numerous. It always stands ready to receive grain for which there is no immediate need, thus equalizing supply and demand. It stands ready to supply the needs of the miller, maltster, manufacturer, or distiller whenever daily arrivals in the market place are insufficient. It holds parcels of grain which can be transferred from seller to buyer by endorsement of warehouse receipts. It moves grain from one mode of transportation to another, as desired; from truck into boxcar, from car to steamer, from steamer to canal barge, from barge to ocean liner. It provides a place for the storage of grain delivered in fulfillment of future contracts.

A terminal elevator assumes a large part of the risk of losses resulting from deterioration during storage, and sometimes, when the operator owns the grain the elevator handles, it assumes market risks as well. Finally, it provides a public warehouse where any producer or subsequent owner may store grain in safety and security until he wishes to sell or use it, and when that time comes, the grain is quickly available.

A typical example of the handling of grain in a terminal elevator will first be described. The construction and uses of the various facilities will then be studied. Some of the daily operating problems will next be discussed, followed by an account of some of the difficulties and

hazards involved in terminal elevator operations. Finally, a rough summary of present terminal elevator capacities in North America will be presented.

General Description

The arrangement of the several parts of a terminal elevator is subject to considerable variation, but in the most conventional plan the elevator is divided into two sections (10). The first is a building called the "workhouse" or "headhouse." It contains the grain-handling machinery, such as unloading and loading equipment, and weighing, cleaning, drying, and elevating equipment. The second part is the grain storage section consisting of bins or groups of bins usually erected as separate buildings. If construction is of steel it is customary to build the bins as individual structures, but where the material is concrete it is customary to group the storage tanks into rows or blocks, and a headhouse may be attached to one or several blocks of bins.

Early terminal elevators were built of wood, which was plentiful and cheap. Storage bins were built up by laying planks flat in piles so that walls were solid wood 8 in. thick at the bottom and 4 in. near the top. Foundations, beams, spouts, roofs, and scales were also made of wood (12). Since this type of construction created a serious fire hazard, other materials soon came into use. A metal jacketing over the wood came first, and bins built completely of steel followed. The slip form for construction of round bins of concrete was developed about 1900, and this method of construction is now in general use. Tile has also been used.

Bin Section. The slip form (10) used in the construction of round concrete bins consists of a concentric double-ring form into which concrete is poured. As the concrete in the lower part of the ring sets, the forms are jacked upwards and more concrete is poured in. The process must go on without interruption until the desired height is reached. It produces a bin in one solid and continuous piece of concrete, without joints or patches. As these round bins are usually constructed in rows so that straight-line conveyors can serve a group of them, a whole series of bins, each with its own slip-rings, may be built simultaneously.

Often two or more rows of round bins are built side by side to form one block of bins. If construction is of concrete, the areas between the circles also become bins, and may be used for storage. They are called interstices, or "star" bins. Sometimes the indentations between the circles of the outside rows of the block are walled off to form additional small bins, sometimes called "pockets." When construction is of steel, however, these star bins and pockets cannot be used.

There seems to be no formula for the best height for storage tanks.

Concrete tanks have been built at heights of from 80 to 140 ft. Factors affecting the height chosen include the ground area available, the storage volume desired, the weight the earth will bear, the cost of elevating compared with the cost of conveying, and the type of workhouse that is to be used. Steel bins are always round, and though some other shapes, such as oval or hexagonal, have been tried with concrete, the round form gives the greatest strength for the least material.

The designer must also decide whether his bins will have hoppered or flat bottoms. Hoppers with sloping floors are convenient, since they are self-cleaning and do not require shoveling. Flat bottoms are cheaper to construct, and give slightly more storage space, but cause some delay in loading out, as shoveling is slow. In general, if bins are likely to be completely emptied more than three times a year, hoppered bottoms are best.

Another question to be decided is the size of the bins. Since the cost per bushel of storage space goes up sharply as bins become smaller, the tendency is to build larger bins. However, small bins also have advantages. A better separation of grains of varying qualities may be made in small-bin storage. If large bins cannot be kept fairly well filled, much of the storage space is wasted. It is usual, therefore, to build the bins in graduated sizes. Quite often we find bins having capacities in the ratios of 5–10–20–50, so that by using one or more bins, lots of almost any size can be made to fit capacity without wasting much space. Similarly, if a large bin has been partly emptied, there will usually be a smaller bin to which the grain that is left can be transferred, thus making the entire capacity of the larger bin again available. In actual practice, the availability of bins of several sizes, instead of just one size, increases effective storage space by about 15%.

Auxiliary Bins. The pressure of grain surpluses requiring safe storage for long periods sometimes leads to the construction of an auxiliary bin of large capacity in connection with a terminal elevator. This has been done in the United States, in Canada, and in Argentina. The purpose of this type of construction is to provide storage space at the lowest possible cost of construction. In order to attain that objective, the auxiliary bins are always arranged so that the weight of the stored grain rests directly on the ground, handling equipment is kept at a minimum, and the roof tends to follow the slope of the pile of grain. Sometimes the temporary storage consists of nothing more than a shed-type sloping roof just sufficient to cover a pile of grain near the elevator. Sometimes large bins are directly attached to the elevator and are covered by a roof sloping from the top of the elevator to the ground. Often the bins are of the quonset-hut type with a rounded roof (Fig. 2).

Sometimes they have no direct connection with the elevator, and grain must be loaded into the bins and removed from them by portable or temporary equipment. More often there is permanent equipment for conveying grain into the storage bin, but temporary equipment for taking it out. When auxiliary bins are directly attached to an elevator they may, of course, have permanent equipment for conveying grain into and out of the bins.

Fig. 2. An example of auxiliary storage at a Chicago elevator.

In the United States and Canada auxiliary storage bins may range in capacity from 200,000 to 1,000,000 bu. each. Sometimes an attempt is made to divide such bins into sections by partitions or low walls, but usually the entire structure consists of only one bin. In Argentina considerable quantities of grain have been stored during surplus years in large trenches in the ground. The sloping walls of the trenches were sealed and the pile of grain was covered with paper, sealed, and then covered with earth.

As noted above, the particular advantage of the auxiliary bin is its low construction cost. It must be emphasized, however, that the advantages of the low construction cost can only be realized if the entire

capacity of the bin is used for a considerable period. It is often difficult to accumulate a single lot of grain of sufficient size to fill one of these bins, and when only smaller lots are available the bin will be only partially employed. Large lots are generally available for only a short time, and the storage space must then be wasted during a considerable part of the year. Where handling capacity is very low, it takes a long time to fill or empty one of these auxiliary bins, and this adds to the costs. Further, special care must be taken to store only sound grain in this type of bin since handling is often slow and because one heating spot, endangering a very large quantity ‹ . grain, may be difficult to reach without removing the entire contents of the bin.

Behavior of Grain in Bins. Clean, dry grain in a pile will flow out to an angle of about 28°, sometimes referred to as the "angle of repose" (11). Damp grain, or grain containing much dockage, will form a slightly steeper angle. The presence of chaff or dust, or of many broken kernels, also increases the steepness of the angle. Some of the heavier grains of uniform kernel size, such as soybeans, will flow out to a slightly flatter angle. The slope will be a little steeper when the bin is first filled, but settling flattens it in time.

This angle of flow forms a conical pile, with its base limited by the walls of the bin, and with its apex at the center of the filling stream. Therefore, if the stream entering a bin is in the center of the bin, grain may be poured in until the cone reaches the point of entry, but the grain will slope away at 28° to the walls of the bin, and the space around the cone will be wasted unless filled by other means. If the stream enters the bin near one wall, even more space is wasted.

Similarly, the hopper at the bottom of a round bin must be cone-shaped, with a slope greater than the angle of repose (12); and the smaller the bin, the steeper must be the angle, because of the wedging action of the funnel-shaped hopper. Any hopper wastes space, as noted earlier, though a hopper with its lowest point in the center of the bin wastes least.

All grain settles or packs in storage. Clean, heavy wheat may pack only 0.6% of its volume, while lightweight oats may pack as much as 8%. Some of this packing takes place when the bin is first filled, and is due to the grain's own weight, though some settling goes on during the entire storage period. Part of this settling is probably due to vibration from passing trains and part of it to collapse of stored materials such as hulls, stems, beards, germ-points, or even the kernels themselves.

It might be expected that the pressure on a layer of grain, and hence the shrinkage in specific volume, would be proportional to the height of the grain above. But this is not the case, because much of the

weight of the grain in a bin is supported by the walls. Each kernel rests on several kernels below it, so that some of its weight is distributed laterally, until this outward pressure reaches the bin walls and rests on them (12). This is responsible for the tendency of grain in a bin to arch or bridge from wall to wall, at least until the draw-off gate is opened, when the bridge effect is reduced, and more of the weight rests on the bin floor until the gate is closed.

Grain tends to separate into heavier and lighter components when poured into or drawn from a bin. When entering a bin, the stream falls freely to the surface of the pile; but the heavier grains fall straight down, whereas the lighter material floats outward. This tends to cause chaff, dust, and lighter particles to accumulate toward the bin walls. When the stream of heavy grain reaches the pile, smaller particles such as weed seeds, broken kernels, and heavy dust particles are trapped between the larger kernels and remain at the center of the conical pile, while the kernels of grain flow away down the slope. This produces a core of high-dockage grain in the center of the pile. Again, when the grain is drawn from the bin, the lighter particles tend to lose their places in the flowing stream and thus to leave the bin last.

When the draw-off gate is opened, the column of grain directly above the opening flows out first. This column widens toward the top of the bin, but grain in the center of the column flows fastest, so that a cone-shaped depression appears on the surface. Grain from the surface flows into this depression and thence down to the draw-off. Hence, the first grain to leave the bin is a narrow core directly above the gate, the next is the surface grain, followed by the progressively exposed surfaces until the bin of grain has literally turned itself inside out, the grain stored in the hopper leaving the bin last.

The Headhouse. The heart of a terminal elevator is the headhouse, for here most of the machinery is found and most of the work is done. The headhouse is usually a rectangular structure built at the end of a block of storage bins or between two blocks of bins. Since the headhouse must also be close to transportation facilities, the whole elevator is generally located between steamer docks and railroad tracks, or between truck driveway and barge dock, or some combination of these.

Near the center of a typical headhouse, a number of elevating legs rise from the basement to the top of the building. The upper floors are occupied by garners, scales, and equipment for distributing grain to the storage section or to bins in the lower part of the headhouse. All this portion rises above the adjacent storage bins, reaching a height of 150 to 200 ft.

Directly beneath the distributing floor of the headhouse are the

shipping and processing bins. The two outer lines of bins along the length of the building are used as shipping bins, since it must be possible to drop grain from them into boats, barges, boxcars, or trucks, as the case may be. The inside bins are used for holding grain on its way to or from cleaners, dryers, and washers.

Below the bin section are floors containing machinery for cleaning grains and separating screenings. All these machines are connected by the ducts of the suction system to dust collectors, and by a system of spouting which finally carries cleaned grains and by-products to the boots of the elevator legs in the basement. To these legs also come all the grain and screenings removed from the storage bins for shipment or processing and, in most cases, all the grain received by the elevator. They reach the boots by means of a system of conveyor belts, often quite elaborate, which travel in underground tunnels.

The layout and functions of the headhouse will be made clearer in other parts of this chapter, but it should be mentioned here that many headhouses do not conform to the foregoing description. In its simplest form, found in elevators whose function is merely to transfer grain from one transportation system to another, the headhouse may consist of nothing more than a single leg and scale, sometimes without even a housing around them. In some of the largest terminals, on the other hand, there may be as many as 24 legs and 18 scales, with correspondingly large numbers of garners and cleaning machines, together with the equipment required for clipping oats and for washing, sizing, and bagging grains. Drying equipment may also be installed in the headhouse, though it is more usual to have it in a separate, nearby building.

Handling Equipment

Capacities. Handling capacity must be related to storage capacity. Where most of the grain is received and shipped via railroad, the typical terminal has receiving capacity sufficient to fill its storage space in about 40 two-shift working days. Terminals in one-crop areas often have receiving capacity higher than that, in order to fill the houses while the crop is moving from the field. On the other hand, houses farther from producing areas or in the path of continuous grain movements may have much less receiving capacity. Truck-unloading capacity at terminal elevators is increasing, but has not yet reached a point where it may be related to storage capacity.

Handling capacity must also be related to the transportation facilities. Where Great Lakes steamers or export vessels are loaded or unloaded, it is desirable to be able to handle one vessel in a day. At trans-

fer houses, where grain is moved from steamer to cars or barges, it should be possible to load grain out of the house as fast as it is received.

Each piece of handling equipment should be related in capacity to every other piece in the elevator. In describing the various items of handling equipment, this will be pointed out. Table I shows a typical example of the handling capacities for various operations in a single-unit terminal elevator.

TABLE I

HANDLING CAPACITIES OF A TYPICAL SINGLE-UNIT TERMINAL ELEVATOR

Operation	Handling Capacity	
	Per Hour	Per 8-hour Day
		Bu.
Unloading trucks	10 trucks	32,000
Unloading cars (shoveling)	2 cars	25,000
Unloading cars (dumping)	8 cars	100,000
Unloading barges	7,000 bushels	56,000
Unloading steamers	12,000 bushels	96,000
Transferring from bin to bin	15,000 bushels	120,000
Drying or cleaning	1,000 bushels	8,000
Loading trucks	10 trucks	50,000
Loading cars	8 cars	100,000
Loading barges	10,000 bushels	80,000
Loading steamers	15,000 bushels	120,000

It must be admitted that the handling equipment of a terminal elevator is seldom efficiently used. This is because capacity must be provided to take care of peak loads that are rarely of long duration. Storage capacities tend to be filled in surplus years, but to remain only partially filled in years of low production. Receiving equipment may be used to its limit for several weeks or even several months of the year, but seldom continuously. An export elevator may load a boat a day for several days, and then none for weeks. One week rail-loading orders may exceed the capacity to deal with them, and the next week such orders may be entirely lacking. Truck-unloading equipment may be going 24 hours a day one week, and be useless the next week because of bad weather.

The same is true of the internal handling equipment. Drying and cleaning may be necessary and profitable for one crop but entirely unnecessary for the next. Conveying capacity needed for efficiently transferring grain may far exceed that needed for unloading trucks or cars.

Unloading and Loading Equipment. The handling and storage of grain in bags is fast disappearing in the United States, and has prac-

tically disappeared in Canada. About the only bagged grain now arriving at terminals is an occasional shipment direct from combines in the field. Considerable quantities are still bagged at export terminal elevators, both for topping-off cargoes, or for entire cargo lots. In South American countries, the major part of the crop is handled in bags during at least a part of its journey from producer to market. In Europe and Australia, much grain is still marketed in bags, particularly where port facilities do not include bulk-handling equipment. Since bag handling is expensive and difficult to mechanize, however, it is everywhere declining in favor of bulk handling. As volumes increase, therefore, bag handling disappears. In these circumstances, the emphasis in this chapter is placed on bulk-handling facilities.

Trucks of bulk grain arriving at a terminal elevator may be unloaded by shoveling or dumping. When shoveled, a power shovel is generally used, which consists of a powered winch that pulls a board about 30 in. high and 40 in. wide. The board is carried to the front end of the load, and pulled toward the tail gate by the winch. This method is largely giving way to various truck dumping devices. In one type, the truck drives its front wheels onto a sling which is lifted,

Fig. 3. A typical car dumper.

thus tipping the truck backwards until the grain pours out. Another type has a platform onto which the truck drives. Chocks block the rear wheels, then the platform is tipped backward until the load runs out.

The same methods are used for unloading grain from railway cars. In the power-shovel type, two winches and two shovels are used, so that one is working in each end of the car, dragging grain out the door at the center. The car-dumper, of course, is a very ponderous affair (Fig. 3), since it must not only pick up and tip the 25-ton car but also pour out the load, which may often weigh 60 tons. To accomplish this the machine grasps the car by its couplings to keep it in place, tips it sideways about 30°, and then tips it from end to end.

After leaving the truck or car, the grain falls into a pit, usually large enough to contain one load. This pit is hoppered to the center or side, so that when the slide is opened, the grain will all flow out. From the pit a screw or belt conveyor carries the grain to the elevating leg in the elevator.

A leg consists of an endless belt, to which buckets are attached, running in a vertical direction. The boot, or lower end of the leg casing, contains a tail pulley under which the belt runs, and as the buckets are swept under this pulley and again start upward they scoop up their

Fig. 4. A tripper for discharging wheat from a conveyor belt to a bin.

loads of grain. When they reach the top of the leg, they pass over the head pulley and turn downward, thus dumping their loads of grain into a receiver or garner. From the garner the grain flows to the scales and is then spouted either directly to a bin, or onto a conveyor belt which carries it over the bin tops until a tripper pours it into the selected bin (Fig. 4).

Vessels are unloaded either with a movable leg or pneumatically. A leg works best where the holds of all the vessels to be unloaded are of similar depth and have large hatch openings and no 'tweendecks. Pneumatic devices are more often used where a wider variety of depths and styles of holds are encountered, as for instance between barges and ocean steamers, or when hatches are likely to be small, or when stanchions and decks make parts of the holds difficult of access. Pneumatic devices use much more power than legs, but are somewhat more effective in cleaning up the bottom of the holds. Marine legs dip to the bottom of a hold, but all grain that does not flow into the boot must be moved to it by power shovels or manually.

With either method the grain is usually carried on conveyors to the boot of the main elevating leg in the elevator and transferred to the storage bins in the same way as receipts from car or truck. Sometimes, however, the marine leg is carried in a movable tower containing the garner and scale. From the scale another elevating leg in the tower carries the grain above the storage bins into which it is directly spouted through V-shaped receivers, without any conveying.

Most storage bins are hoppered at the bottom, though they may have a flat floor, which means that to completely empty them some of the grain must be shoveled. In either case, the grain falls from the opening to a screw or belt conveyor in the basement. It is carried to the boot of the leg which elevates it to the garner again. From there it can be returned to another bin, to the dryer or cleaner bins, or dropped down a loading spout to truck, car, or vessel.

Grain to be loaded to cars or trucks is dropped down a long loading spout which has a curved end to spread the load evenly in the vehicle. A clear fall of at least 65 ft. is needed to throw the grain into both ends of a boxcar, but truck loading requires less height. When a vessel is loaded, a shipping bin is usually interposed in the grain stream, so that grain can be weighed into it continuously, the stream from the bin being shut off by the men on the boat whenever they wish to move loading spouts, hatches, or the boat itself.

Now let us return to the problem of relating the capacity of each item of handling equipment to the other items. Since loading capacity is usually required to exceed unloading capacity, a start may be made

with the former. Suppose it is desirable to be able to load a cargo of 300,000 bu. in 10 hours. Since there are always some delays, it will probably be necessary to provide elevating capacity of 40,000 bu. per hour. Legs of that capacity or even larger are in operation, but if such large capacity will not be needed for the other operations the leg will have to perform, such as unloading cars, trucks, or barges, transferring, or loading to cars, it will be better to provide two legs each with a capacity of 20,000 bu. per hour. Each of these must have its complement of garners, scales, spouts, shipping bins, and loading spouts. The draw-off gates on each of the storage bins will have to have the same capacity, or it will be necessary to draw from two or more bins simultaneously and they may not be available. Each conveyor belt under the bins leading to the leg will have to have the same capacity, for though there may be more than one belt, there are bound to be some occasions when only one of them will be available for the desired grain.

The spout from the leg to the garner will also have to take 20,000 bu. per hour. The spout from the scale, however, will have to have twice that capacity, since the scale is employed half the time in filling and half the time in emptying. Each shipping bin should have a capacity of 10,000 bu. and thus be able to receive the full stream from the leg for a half hour in order that the leg may continue to operate while the vessel is being shifted or during other delays. The loading spout from the shipping bin to the boat should then have double the capacity of the leg to allow the bin to be emptied after these delays. It must therefore carry 40,000 bu. per hour.

We now have two legs, each with a capacity of 20,000 bu. per hour, to be used for other purposes when a boat is not being loaded. Each of them could be employed to load 10 cars per hour, for instance. That would require a loading spout for each capable of delivering 40,000 bu. per hour, since each spout will be idle half the time while cars are being shifted and the scale refilled. The two scales could load two cars at a time on the same track, though a better arrangement is to load a car on each of two tracks simultaneously. By that arrangement a delay on one track will not hold up both scales.

Or, we may wish to use one or both of the legs for unloading cars. Allowing for delays between cars, the leg will probably be elevating grain about half the time. It will thus handle about 10,000 bu. or six cars per hour. The ordinary shovel and winch unloading equipment will unload about two cars per hour and so each leg will require three unloading stations or pits. This may even be increased to four pits by making the pits large enough to hold a carload, so that the conveyor and leg may be used with fewer interruptions. If both legs are used for

unloading cars, six or eight pits will be needed to keep them busy. In practice such an arrangement is quite frequently found in the form of two pits on each of three tracks, or three or four pits on each of two tracks.

If a car dumper is to be employed, a leg capacity of eight carloads per hour must be provided since these devices will often unload cars at that rate for extended periods. Because of delays between cars, it will require extremely deft management to handle them on one 20,000-bu. leg. On the other hand, if both legs are used, neither will be operating at capacity.

In terminal elevators where grain is received from trucks or shipped out by trucks, special equipment is usually provided. Even where truck dumps are employed, it is unusual to receive as much as 4,000 bu. per hour, and truck loading goes even more slowly. Since it is wasteful to tie up a leg of large capacity for these purposes, many terminals are provided with truck legs, and also truck bins into which grain can be unloaded, or which can be filled (for loading out) by the main leg and scale.

Conveying equipment inside the elevator must also be of a capacity to fit the main leg. As already mentioned, the conveyor belt from the bins to the leg must carry as much as the leg; the spouts and conveyors leading from the scale into the bins must each have about the same capacity or more. When unloading cars, for instance, this is true even though the grain flows intermittently. If the leg is to be used at capacity for transferring from one bin to another, however, the leg will be elevating grain into the garner continuously while the scale must be employed half the time in filling and half the time in emptying. The spouts and conveyors to the bins will then need to have a capacity nearly double that of the leg.

Scales and Weights. All grain is bought and sold by weight, and all grain entering or leaving a terminal elevator must be weighed. A variety of devices is employed for this purpose.

Grain in railroad cars may be weighed on track scales, where the entire car and its contents are weighed first, then the car is unloaded and the empty car weighed. In some cases, where the scale is not in the elevator tracks, the car and contents are weighed before unloading, and the tare weight which is printed on the side of every boxcar is used. Usually, the scale is somewhere in the elevator's own tracks, often right in front of the unloading pit, so that the car can be weighed both before and after unloading without being moved. This is also a convenient arrangement for weighing outgoing shipments.

A more common method of weighing grain is with the hopper scale

(Fig. 5). This scale is round or square, with a hoppered bottom and large outlet gates, all mounted on the scale beams. The most common size has a capacity of around 2,500 cu. ft., or well over 2,000 bu. It is designed to weigh a carload of grain at a time. In spite of its capacity of 60 tons or more, the modern scale is remarkably precise and often maintains an accuracy within plus or minus 0.01% for long periods. The beam of the scale is placed conveniently for the weighman or operator and the load is balanced by one sliding weight. When the scale is in balance, the operator inserts a scale ticket of soft cardboard, and a clamp presses it against the raised figures on the beam so that the weight is imprinted on the ticket, making a permanent record.

Hopper scales are variously located in terminal elevators. Most often they are at the top of the workhouse, just beneath the head of the leg.

Fig. 5. Partial view of a 2000-bu. scale.

One leg may be fitted with two scales, so that the feed can be directed into one or the other. Usually, however, there is one scale per leg with a garner above it of equal or greater capacity, so that the stream of grain from the elevating leg may be continuous, while the scale is filled intermittently from the garner. Some installations have a garner below the scale as well, so that the rate of emptying the scale does not have to be limited by the capacity of the spouts or conveyors below it. Many garner and scale gates are of such capacity that the scale can be filled in less than two minutes, or emptied in less than a half minute. In the older houses these gates were manually operated with long levers, but in more modern types they are pneumatically or hydraulically operated for faster and more positive action.

The scale may sometimes be placed on the ground floor in the headhouse. Grain from cars is then elevated into it with a short leg called a "jack-leg," and after being weighed is elevated on the taller leg to the top of the storage bins. When loading out, the jack-leg fills the scale, and then the grain is elevated and dropped into the car. While the placement of the scale at the top of the workhouse calls for more expensive construction, it has several advantages. The double elevation necessary with the scale on the ground floor is avoided, and the scale may be used for other purposes, such as weighing transfers, or grain going to cleaner or dryer bins, or to the shipping bins for boat loading.

The movable unloading equipment called "marine towers," found in some terminal elevators, is usually fitted with scales having capacities up to 500 bu.

Incoming and outgoing shipments by truck are weighed in various ways. Sometimes we find a platform scale in the roadway approaching the unloading pit on which the trucks are weighed before and after unloading. Sometimes the truck-dumping platform is itself a scale platform, and the truck can be weighed before and after unloading without moving. Sometimes the pit into which the trucked grain is shoveled or dumped is the scale hopper, and sometimes the grain may be elevated into a small hopper scale, either on the ground floor or above the storage space. All these scales except the pit scale may also be employed for loading trucks as well as unloading them.

Small automatic scales having capacities of from 1 to 5 bu. are sometimes employed. They fill to a prearranged limit, then shut off the grain stream and dump their load. Each scale load is called a draft, and a counter on the machine records the number of drafts the scale has dropped. This type of scale is used for bagging, for loading trucks from truck bins, for grain being cleaned or dried, for corn from shellers, and similar weighing jobs. Even though such a scale may drop 10 drafts a

minute, its capacity is still small, and its accuracy never matches that of a larger hopper scale.

Grades and Grain Inspection. We have discussed methods of determining the quantity of grain arriving at or leaving a terminal elevator; its quality must be determined with equal care.

Since terminal elevators deal with large quantities, and only a small portion can be carefully examined, the first requisite is to get a representative sample. Grain in a car or a truck is usually represented by a single composite sample. Grain in barges may also be graded on one sample, but more often several samples are used. When these are taken during loading or unloading, each commonly represents 10,000 bu.

Samples may be drawn by several methods. The most common device is called a probe. This consists of two concentric tubes, about 5 ft. long and 1½ in. in diameter, into which a series of openings are cut. The inner tube is turned until its openings are hidden, the probe is pushed into the grain, and the inside tube is then turned again until the openings match those in the outside tube when grain runs in and fills the tube. A further rotation closes the openings and the probe is withdrawn. Carloads of grain are customarily probed at five points, and truckloads at three to five points. A longer probe, sometimes 10 ft. in length,

Fig. 6. An automatic sampler; the cups on the moving chains pick up samples from the stream of grain.

is used for sampling barges.

Grain in bins may be sampled by a device called a bucket probe, which is a short tube fastened on the end of a jointed rod or pipe. It is forced to the desired depth in the grain, and is arranged to open when the rod is pulled. Grain being loaded to a boat is often sampled with a "pelican," a leather bucket on the end of a pole, which is cut across the falling stream below the end of the loading spout. Samples are often taken from grain on a moving conveyor belt by scooping handfuls out of the stream. Automatic samplers have been devised, and are coming into considerable use, particularly in Canada (Fig. 6). Whatever the device, the sample taken is quite small, being about one part in 5,000 in truck sampling and one part in 100,000 in cargo sampling. In spite of that, the representative character of the samples is rarely questioned.

For trading purposes quality is established by inspection of the samples, or of portions of them, and by making a few relatively simple tests to determine the test weight, moisture content, and the percentage and nature of other kinds of grains, weed seeds, and other foreign material that may be present. All the damaged kernels in a small subsample are examined and the amounts found are expressed in percentages. The presence of any abnormal odor is noted. In wheat samples protein content may be determined, and in oil-bearing seeds the oil content may be measured.

In many grain-producing countries these quality factors are used to establish the grade of a sample, which is indicated by a number. In the United States the grade specifications include the minimum test weight, the maximum moisture content, and the maximum allowable percentage of foreign material, damaged kernels, and other classes of grain. They also contain clauses with respect to garlic, smut, insects, and certain color determinations. These specifications were established by Act of Congress, August 11, 1916 (23) and remain relatively unchanged from year to year. The Canadian grading system is similar to that of the United States; it differs mainly by specifying the total amount of damage permitted in each grade rather than by specifying maximum for each individual type of damage. In some other countries, all the grading criteria are not so rigidly fixed, but may be varied somewhat from year to year, according to the quality of the current crop. Whatever the exact procedure, the standards are set by governmental agency and the ultimate purpose of the system is to provide a means by which the quality of any parcel of grain can be stated in simple terms for marketing purposes.

These grading methods are in daily use at all terminal elevators. Incoming grain is inspected to see that it has been properly graded. Grain

in store is frequently inspected to see that the grade is unchanged, or to determine how much it has been improved by processing. Grain leaving the terminal is likewise inspected to be sure it is of the required grade.

Cleaning Equipment. The term "cleaning" includes a variety of operations. It may refer to the separation of weed seeds or other impurities, to classification of kernels by length or width, to the separation of various kinds of grain from each other, or to washing. Each kind of grain and each impurity is a separate problem, but, in general, only three cleaning methods are used in terminal elevators. These involve the use of aeration, perforated screens, and indents.

In aeration, a lighter material is separated from a heavier material by a current of air. Some machines employ this principle only and have large cleaning capacities; others combine aeration with other cleaning methods. A clear-cut separation is seldom achieved by aeration and it is used mostly for removing dust and chaff, or assisting the other methods. Nearly all types of cleaners provide some aeration.

Perforated screens are the main feature of most cleaners. The grain is allowed to flow in a thin stream over a screen with holes or slots designed to separate the impurity, while the screen is vibrated, usually in the direction of flow. Sometimes slotted screens are used to separate thin kernels from plump kernels of the same kind of grain, or different grains from a mixture, or seeds or broken kernels from whole kernels, or other foreign material from grain. One machine uses rows of wires, fixed at one end, and spaced at fixed distances, over which the grain flows by gravity; it is designed to do many of the jobs that slots in screens will do. Its advantage is that with the wires free at one end they will not plug. Another machine has wires carefully spaced and curved to form a rotating drum through which the grain flows.

To separate kernels of various lengths, pockets or indents are employed in several kinds of terminal cleaning machinery. These indents may be on the faces of disks, which are rotated on a horizontal axis so that their lower parts move through the grain. Sometimes the indents are on the insides of cylinders which are partly filled with grain. Only grain of the desired length will fit into the indents, and be lifted out of the grain mass and spilled into prepared receivers.

Grain washers use a spray of water to rinse the surface of the kernels, carrying away undesirable substances. The principal use of washers in terminal elevators is for the removal of smut from wheat.

Dryers. Nearly all terminal elevators include in their equipment some device for the artificial drying of grain. The grain dryer is probably used less steadily than any other piece of equipment, however, because most crops dry naturally in normal years to a reasonably safe storage level.

There will be some areas every year where artificial drying is needed, but even in these areas the dryers will probably be required for only part of the year. Consequently, the average dryer is probably not in use over 10% of the time.

The principle of all types of dryers is the same. The kernels of grain are exposed to air in which the relative humidity has been lowered by artificial heating. In one type, a compartment is crisscrossed with shelves or louvers which allow the heated air to flow through the grain when the compartment is filled. Another type has the same arrangement but the grain flows continuously over the louvers while heated air passes through. Another device has columns of grain between walls formed of perforated screen; heated air is passed through the screen as the grain flows down the column. Horizontal cylinders are sometimes used, which are rotated while the drying air is passed through and over the grain. Perforated belts are arranged to carry grain over a source of dry air. A method of drying in a partial vacuum has been patented in Germany. Drying with natural air in small bins or cribs is occasionally practiced, though seldom in the terminals.

Steam coils heated by coal furnaces were formerly the most popular source of heat, but direct-heat oil or gas furnaces are coming into wide use. When the latter are used, the hot gases from the flame are mixed with natural air to the desired temperature, and the mixture forced directly through the grain. Air temperatures used in some dryers go above 200°F., though the temperature of the grain seldom approaches such a high level. Much of the heat carried by the drying air is used to raise the temperature of the grain.

In seed drying, where viability may be damaged by high temperatures, much lower air temperatures must be used because the surfaces of the kernels, including the germ area, may approach the air temperature even though the average temperature of the kernel may be relatively low. Under such conditions the efficiency of the dryer may be partly maintained by increasing the air volume.

In Canada, all grain drying in terminal elevators is controlled by the Board of Grain Commissioners. Regulations require that the temperature of the hot air be measured with a recording thermometer at a suitable point in the main air stream before it enters the grain chamber. The air temperature must not exceed 110°F. for drying malting barley, nor 180°F. in drying other grains. The Board's grain inspectors supervise all drying operations, and have the assistance of the Board's Research Laboratory in ensuring that no damage to grain quality is caused by drying.

While the principal use of grain dryers is to reduce the moisture

content of grain to a safe storage level, they may also be used for drying grain to moisture levels desired by a processor. Or, by passing unheated air through the grain, they may be used for cooling grain or removing foreign odors.

Whenever convenient, dryers are placed outside the headhouse, but close enough so that they can be served by its elevating equipment. Housing them in a separate building decreases fire hazards, and is more convenient in other ways. Since the capacity of a single-unit dryer of any type seldom reaches 1,000 bu. per hour, most dryers are preceded by garners of sufficient capacity to supply grain to the dryer for at least an 8-hour period, so that elevating equipment needs to be employed in servicing the dryer only once a day. Some installations also have a garner below the dryer, but more often there is an elevating leg of small capacity to transfer the dried grain to a storage bin.

Costs of artificial drying must be carefully considered. The direct costs consist of heat, power, and labor, and are easily measured; but the indirect costs of repairs, depreciation, insurance, and interference with other elevator activities are more difficult to assess. In addition, there are the costs of shrinkages caused by losses of both moisture and dry material, which are often underestimated. Actual loss of dry material in the customary commercial drying operation is about 0.4%, and though this loss consists of dust and chaff, the cost of the final product is increased accordingly. The shrinkage due to loss of moisture can be calculated from the following formula:

$$\text{Percentage loss in weight} = \frac{100\ (M_1 - M_2)}{100 - M_2}$$

where M_1 is the original moisture, and M_2 is the moisture content of the dried grain.

Temperature Measuring Systems. The prudent terminal elevator operator will want to follow the temperature changes of the grain he has in store. The most common method of accomplishing this is to bury thermocouples in the grain. Pipes are either hung in the bins before filling, or pushed into the grain after it is in storage. The thermocouples are inserted into these pipes. In more elaborate installations, each storage bin is permanently equipped with one or more pipes, and thermocouples are strung in the pipes at 5-ft. intervals. The leads from all the thermocouples are carried to a central board, where an operator may read the temperature of any spot in any bin in the elevator, by making contact between his instrument and the appropriate pair of wires. Less elaborate systems employ portable potentiometers, and may use only one thermocouple, which is lowered to various depths in the

grain through the pipes. A recent development has the thermocouple and reinforcing wires encased in a plastic covering, so that the pipe is not necessary. Other methods of checking temperatures include lowering a thermometer on a string into a pipe buried in the grain, or pushing a thermometer in a protective case into the grain.

It is often desirable to get information as to the temperature of grain piled on the ground, or stored in auxiliary or temporary bins, quonset huts, flat warehouses, vessels, barges, etc. The usual method is to push a pipe to the desired location, insert a thermocouple, and read the temperature by means of a portable potentiometer. Thermometers may be inserted into the pipes instead, or thermometers on the end of pipes or rods may be inserted in the grain, withdrawn, and read.

Dust-Collecting Systems. A terminal elevator would be a very dusty place if it were not for the dust-collecting systems. Grain arriving at the elevator always contains considerable quantities of fine particles mostly from the bran coats of the kernels, but also from hulls, stems, leaves, as well as dust and sand from the field. As a result of handling large quantities of grain at high speeds, still more dust is produced by abrasion. Clouds of dust arise from the unloading pit, the conveyor belts, the legs, garners, and scales, and the grain entering a bin blows back its own volume of dust-laden air. Without dust collection a high-speed grain stream in a modern terminal will deposit an appreciable layer of dust on nearby floors and walls within an hour. A dust-collecting system thus reduces sweeping costs. By decreasing the explosion hazard it also lowers insurance costs.

The dust-collection system in a terminal elevator works like a gigantic vacuum cleaner. The suction is provided by a central fan or fans, and pipes lead to the points where dust is produced—pulleys at the head of conveyor belts, leg heads, belt-loading spouts, trippers, garners, scales, and bins. Much of the dust is sucked into these pipes as soon as it is produced by the movement of the grain and the rest is removed as fresh air is drawn in from the outside.

Dusty air thus collected is blown through settling chambers and into cyclones. The settling chambers are simply enlarged places interposed in the air line to catch heavy particles, such as whole kernels of grain. The cyclone, which is made of sheet metal, has a cylindrical section at the top. As the dusty air enters this section it expands and a whirling motion is induced. Contact with the sides of the cyclone reduces the velocity of the air. As a consequence of this loss of velocity the dust it carries is released and falls down the hoppered sides of the lower part of the cyclone into the dust bin beneath. The free air escapes from an outlet at the top.

Some grains will lose as much as 0.1% of their total amount as dust. The dust system may pick up two-thirds of this, so that a terminal handling as much as one million bushels a day is likely to collect up to a 40-ton carload of dust every other day in its dust-collecting system.

Power Sources. The earlier terminals were nearly all powered with steam engines. Each had its separate powerhouse near the headhouse, with a tall smokestack alongside. Power was transmitted through the elevator by a line shaft, which ran across the headhouse floor. It carried pulleys at appropriate places to supply power by belt or rope drives to unloading shovels, conveyor belts, legs, and cleaning machines. As the terminals grew in size, this transmission system became quite complex and its maintenance was probably the greatest single operating problem.

That system eventually gave way to the use of individual electric motors, placed wherever power was needed. An intermediate arrangement found one very large electric motor replacing the steam boilers, but as soon as dustproof motors that were not an explosion hazard were developed, they began to replace the cumbersome single power unit. Now it is usual for each piece of moving machinery to have its own motor. Usually the source of power is purchased electricity, but some terminals produce their own power with diesel-electric or steam plants.

Terminal Elevator Operation

In this section an attempt will be made to describe the management and operation of a typical terminal elevator, to say something about its sources of income, to discuss the ownership of grain it handles, and the purposes of the various operations it performs. This will be followed by a description of the flow of grain through a terminal, and discussion of certain operating problems.

Ownership and Operation. There appear to be four general classes of terminal elevator operators. They are governmental agencies, transportation agencies, warehousemen or grain merchants, and processors.

Terminal elevators owned by governmental agencies are located in most instances at places where they appear desirable as a necessary link in marketing channels, and where private enterprise cannot find sufficient capital or incentive to provide the needed facilities. Frequently they are a part of harbor or waterway development projects. Sometimes they are also operated by the governmental agencies, in which case they provide grain storage and handling services for public use. Sometimes they are leased to private operators, who then must operate them as public warehouses, but may also handle their own grain.

Transportation agencies sometimes provide terminal elevators some-

where on their lines to induce the movement of grain via their facilities. They also may operate the elevators themselves as public warehouses, or lease them to other operators.

Private owners, however—individuals, corporations, or cooperatives—are probably the largest class of operators. In any case, the owners usually act both as public warehousemen and as grain merchandisers. As public warehousemen they store and handle grain for its owners, who may be producers, investors, speculators, or government agencies. As grain merchandisers, they combine their facilities for storage and handling with a strategic location between transportation facilities, or between areas of supply and demand, in order to profit from their ownership of the stored grain.

Processors frequently have terminal elevator facilities attached to or near their processing plants. The principal object is to provide space for the storage of supplies of grain acquired during periods of crop movement or low prices for use during periods of scarcity or high prices. A secondary object may be to have a sure source of supply independent of fluctuations in deliveries caused by transportation delays and other factors.

Whoever the operator may be, the problems of elevator management are quite similar. Briefly, they are (a) to make the most efficient use of the storage space and handling facilities of the elevator, (b) to keep costs below income, and (c) to avoid serious losses as a result of deterioration in grain quality or property damage. In order to explain the first problem, the normal flow of grain through a terminal elevator will be described, noting the points that must be watched in order to make the best use of available facilities.

Normal Flows. Careful planning is the key to efficient use of elevator facilities. Each day's work must be planned in advance, even though it is quite likely that the best-laid plans will not be carried out exactly. A normal day at most terminals contains several quick changes in plans, and a consequent reorganization of the balance of the day, to take care of unexpected orders, to avoid delays, or to work in an extra activity. In spite of that, the elevator superintendent needs as much information as possible about the work load ahead of the elevator in the way of car unloading or loading, truck grain to be received or shipped, or vessels arriving or to be loaded out.

Usually, tentative plans are made the day before. Cars must be ordered to be placed on track during the night; samplers, inspectors, weighmen, boat trimmers, car coopers, if needed first thing in the morning, must be notified the day before. If bins need to be emptied by transferring in readiness for the next day's unloading, that work may

have to be done during the night. Loading orders must be checked to see that proper warehouse receipts have been canceled, and that the loading date is correct. Internal operations such as cleaning, drying, transferring, and conditioning are reviewed, and the necessary items put into the morrow's program.

If the elevator has just a single leg and scale, only one operation can be performed at a time, and planning must concentrate on first things first, on avoiding loss of time when changing from one operation to another, on combining small jobs into larger ones, and on doing each operation at the upper limit of equipment capacity. If the house has several legs and scales, and numerous conveyor belts and other equipment, planning must provide simultaneous work for as much of the equipment as possible, each operation must be carefully timed so that another job is ready on its completion, and single operations that tie up all the equipment must be avoided.

Let us now follow a carload of grain from its arrival at a terminal through the unloading, weighing, binning, transferring, cleaning or drying, and reloading operations. It is assumed that these operations take place in the United States. Conditions differ in other countries; for example, in Canada all official sampling, grading, and weighing are done by the Board of Grain Commissioners.

Before the car arrives at an elevator in the United States, it has been stopped in the railroad yards where representatives of the state or the grain exchange open and sample it. The sample is inspected and graded by licensed inspectors, and the car then ordered to the elevator. On its arrival there it is identified by grade and by owner, and quite often resampled and inspected by the elevator crew. If the grade is correct, and if there is a place for the carload in an empty bin or in a partly filled bin of the same grade and quality, the car is unloaded. The doors are opened and the top grain door removed so that as soon as the pit is clear and the car spotted, unloading may start.

The pit is checked to be sure it is empty, and the gate closed. The grain is shoveled or dumped into the pit, the car swept out, and grain doors returned to the car. As soon as the previous carload is out of the garner the weighman closes its gate and signals the foreman on the unloading tracks, who opens the pit gate. The grain then flows onto the conveyor beneath and is carried to the leg, where the buckets scoop it up and carry it to the top of the elevator. When the buckets pass over the head pulley and turn downward, the grain is thrown out, collected by a hood and led down a spout to the top of the garner.

When the pit is empty, the track foreman signals the weighman who, after checking his scale to see that it is empty and the gate closed, opens

the garner gate, allowing the grain to flow into the scale. While the scale is filling he prepares a blank scale ticket with the identification of the car, so that as soon as the carload is all in the scale he can balance the beam and insert and punch the scale ticket. At the same time, the supervising agencies (and sometimes a representative of a railroad or insurance company as well), check the balance of the beam and record the weight. Meanwhile the weighman has received orders as to the disposal of the carload, and has communicated these instructions to the spoutman on the top bin floor by voice-tube, phone, or written order. He, in turn, has arranged spouts and conveyors to lead the grain to the proper bin, checked to see that there is room, and signaled the weighman that all is ready for the car. The weighman then opens the scale gate and the grain flows down the spouts and along the conveyors until it spills into the proper bin.

When the first carload of grain is put into a bin the superintendent marks that bin on his binboard (which is a diagram of the storage space) showing the grade, all factors of quality, and the date. He then attempts to put into that bin only other carloads that are quite similar in all respects to the grain already there, so that the bin will be filled with grain of uniform quality. Since no two cars of grain are identical, however, some compromises must be made and these will depend upon the number of bins available. When there is plenty of room, grain can be classified on the basis of small differences in quality, but as the elevator fills up, fewer bins are available and the grain in each bin becomes less and less uniform. If possible, however, there should always be at least one empty bin to accommodate a carload of grain which cannot be put into any partly filled bin without causing a serious loss. In passing, it may be noted that the Canada Grain Act and most supervising agencies in the United States require that certain grades of wheat "shall be binned with grain of the same grade and not otherwise."

After the car is unloaded, its weight is recorded and added to the stocks. The warehouseman writes a warehouse receipt to the owner of the grain. This is simply a statement of the amount and quality of the grain that has been received and will be delivered to the holder of the warehouse receipt on his order. The supervising weighman makes a certificate as to weight, while the grade has already been certified by the licensed inspector. The grain has now lost its separate identity. While it remains in the bin, its condition must be watched carefully, a problem which will be discussed later.

If the grain is to be cleaned or dried, it must be transferred to the processing bins. The gate at the bottom of the bin is opened, allowing the grain to flow onto the conveyor which carries it to the elevating leg.

After elevation it flows through the garner and scale, and down prepared spouting to the proper bin. From there it is drawn by the cleaner or dryer operator to fit the capacity of his equipment, and after processing passes into bins below, or up elevating legs into other bins. Shrinkages sustained in this processing must be carefully measured and samples of the finished product must be inspected at regular intervals to see that the required level of quality is being attained.

When grain is to be loaded, many preparations must be made. A loading order from the owner of the grain is the first requisite, and must be accompanied by warehouse receipts or proof of their cancellation. An empty boxcar must be ordered and, on arrival, prepared for loading by coopering and lining with paper. Supervising weighmen and samplers must be on hand. If, as is common in the United States, the loading is to be a mixture from several bins to make a specified quality, the mix must be carefully figured and the feed-tenders advised. When all is in readiness, the gates are opened, grain flows along the conveyors and is lifted up the legs until the weighman has the required amount in the scale, when he signals the feed-tenders to close the bin gates. After the beam is balanced, a scale ticket is punched and the supervising weighman checks and records the weight. A signal informs the track foreman that the carload is ready. When the prepared car is in position under the loading spout a return signal is sent to the weighman who opens the scale gate to allow the grain to flow down the loading spout into the car. When the scale is empty, the grain in the car is leveled and sampled and the car doors are closed and sealed. The sample is inspected and if found to be of the proper grade the car is billed.

In all this movement of grain, capacity measured in bushels per hour is most important. The exact capacity of every piece of equipment should be known and, if possible, all equipment should be used at full capacity. There is a point, however, at which elevating legs will plug or grain will spill or equipment break down and stop the whole operation. The aim must be to operate at maximum capacity without incurring these difficulties.

Storage space must be conserved with equal care. Room may be wasted in a number of ways. If too many quality classifications are made, many bins will be only partly filled. If future receipts of a particular kind of grain are overestimated, a small quantity of grain will occupy a large bin. If small bins are used too freely it may eventually become necessary to put small lots into large bins. Loading orders leave bins partly filled. A slow cleaning or drying process will also cause waste of space.

All these situations are found to arise from time to time in spite of

the most careful planning, but fortunately they can be corrected to a large extent by transferring. As the small bins fill up they can be combined into larger bins, leaving the small bins for new small lots. If there is not enough grain of the same quality in small bins, the deficiency may be made up and the quality maintained by blending grains of different qualities to produce a suitable mixture. In such ways, by simple transfers or by blending, storage space can be most efficiently used and working space made available; but again daily study of the problems and careful planning are essential.

Supervision. Supervising weighmen and inspectors have already been mentioned, and warehouse receipts have been referred to. A warehouse receipt is usually a negotiable instrument, and grain may be bought or sold by its endorsement and transfer to the new owner. It is a statement by the warehouseman that he has received and holds in his elevator a certain quantity and quality of grain. That quantity and quality must always be substantiated by official weights and grades. There must be disinterested supervision of the terminal elevator to make the warehouse receipts official.

Supervising agencies in the United States fall into three classes. They are the federal government, the various states, and grain exchanges. Exchanges are usually licensed under state laws; where there is federal supervision, its regulations supersede the states' laws. In Canada, the supervising agency is the Board of Grain Commissioners.

Whatever the agency, methods of supervision are similar. The agency has a representative at the elevator to check and record the weight of all grain received into or shipped out of the elevator, and to certify it. All grain entering or leaving the elevator must be sampled and inspected by representatives of the supervising agency, and those inspectors must be licensed under the United States Grain Standards Act (23), if their grade certificates are to be used for commercial purposes. Usually, the agency maintains a registration service, which checks the quantity and quality shown in the warehouse receipt with its own records and, if found correct, registers it. All agencies inspect the elevator and its stocks at regular intervals. All this is for the purpose of putting the integrity of a terminal warehouse receipt beyond question.

Costs. A terminal elevator represents a considerable investment. Construction of the facilities necessary to handle and store large quantities of grain is very expensive, leading to high costs of depreciation, rent, insurance, and other fixed charges. Before World War II, roughly two-thirds of the costs of handling and storing a bushel of grain in a terminal were fixed costs, and the balance was made up of such operating costs as labor, power, and repairs. This naturally led to an emphasis on han-

dling capacity since a large number of bushels reduced the cost per bushel by spreading the fixed costs.

Today labor rates and other costs have risen until well over one-half of total costs are operating or out-of-pocket costs. This situation will undoubtedly lead to an emphasis on storage as against grain handling, and will certainly stimulate a search for laborsaving devices, and a trend to high-capacity handling equipment of simple design.

Besides the elevator crew, who are trained in the handling of grain or grain-handling machinery, the warehouseman needs a staff for other purposes. He will need samplers and inspectors to assist in quality control. He will need accountants and clerks to keep records of stocks, operations, and costs, pay bills and wages, and to issue and cancel warehouse receipts. He will need millwrights and maintenance men to keep the plant in good repair. Finally, he will need a superintendent and foremen to direct activities. Some of these duties may be combined, or shouldered by the superintendent or outside agencies, but they all must be performed by someone.

Possibly the greatest saving in operating costs can now be made by preventive maintenance. The practice of running machinery until it breaks down is costly in time wasted during shutdowns, and in money for new parts and repairs. A careful and thorough program of checking the condition of all equipment at regular intervals, and maintenance of items needing attention, is now recognized as a better system. Conveying equipment is checked for worn places, alignment, and bearing failure; the elevating legs for loose buckets and torn or worn belting; motors for insulation; scales for condition and accuracy; and roofs and walls for leaks or cracks. All this must be carefully planned and attended to for an efficient program of maintenance.

Operating Hazards

Aside from the daily race between costs and income, there are certain calamities that may overtake a warehouseman, and two types of these will be discussed here. The first is deterioration in grain condition, which may cause losses far exceeding any income for handling or storage the warehouseman may receive. The second group of disasters he may encounter are accidents to his crew or equipment.

Deterioration of Grain Condition. Preservation of grain condition has probably been a problem to the warehouseman since Joseph stored the surplus from Egypt's seven fat years through the seven lean years, but it becomes a really formidable problem when grain is stored in large masses in the modern terminal elevator. A kernel of a cereal grain is a seed, which combines the germ of a new plant with enough food to

start growth. Its function is to survive and reproduce its species in the next season. Meanwhile it must resist the attacks of insects, molds, and bacteria, and remain undamaged through wide swings in temperature and humidity. At the time of ripening it contains extra moisture, which is lost from its surface by evaporation until it is dry enough to limit the activity of microorganisms, insects, and enzymes. Formerly, this natural drying took place during harvesting, while the grain stood in the shock or stack. With the use of the modern combine, however, the grain is harvested and threshed in one operation and hurried off to storage with little opportunity to dry naturally. This has tended to raise the moisture content of grain arriving at the terminal elevator, often to the point where storage is dangerous. For most grains that point is somewhere around 14% moisture, but it varies widely with temperature and other conditions (3).

Grain may go out of condition for a number of reasons, and be damaged in a number of ways. The kernels may be discolored by heat, molds, bacteria, or from causes unknown. Total weight and, in wheat, milling yield and baking qualities may be impaired by insects, heating, or enzymic activity. Even when heating does not occur grain may develop objectionable odors (musty or sour) which carry over into the end products. In oil-bearing seeds, yield and quality of the oil may be reduced. The value of malting grains drops when viability is lost in storage. Certain vitamins and feeding values are lost in long storage under less than optimum conditions.

The most obvious critical factor governing the keeping qualities of grain is moisture content. While no grain is entirely safe from condition losses, the first thing the warehouseman notes is that losses occur more often when the moisture level is above 14%. Research in the laboratory has confirmed that level as approximately the point where the activity of molds takes a sharp upward turn (4, 13, 14, 18, 22), and has indicated that the activity of these microorganisms accounts for much of the heating that takes place in stored grain (6, 9, 17, 19). Accordingly, public warehousemen usually refuse to accept for storage grain with well above 14% moisture unless the owner agrees to allow it to be dried to a safe level; or if the warehouseman is himself the owner of the grain, he, too, will have it dried. He can usually do this without loss because the high-moisture grain has been bought at a discount which covers the cost of drying.

The safe level, however, is not always 14%. It goes up as temperature goes down, so that grain of higher moisture content can be stored in cold climates or during winter. Conversely, it goes down as the temperature of the grain or the outside air rises. It is lower in mixtures of high-

and low-moisture grain than in grain of uniform moisture content, and lower if the grain has been artificially dried, or damaged in any way, and especially in grain that has previously heated. It tends to be higher in starchy grains and lower in oil-bearing seeds. It is lower during spring and early summer, and at some period shortly after harvest when the grain is going through the "sweat," than at other periods of the year. It is therefore not true to say that grain with about 14% moisture can always be stored with perfect safety. It may go out of condition. Yet even when there is a very real risk that this will happen, such grain is not always dried, chiefly because the costs of drying may not be offset by an increase in market value.

Since moisture is such an important factor in the storage of grain, we might examine some points in its behavior in the storage of large masses of grain. One of the most striking is the ease and rapidity of translocation of moisture (1, 7). In a bin, moisture from high-moisture grain will move into dryer grain. In bins of warm grain, moisture will move upward with the air currents during cold weather and deposit at or near the surface. Moisture content usually increases in grain just above a heating spot in a bin. A bin of warm grain stored against a bin of cold grain will cool off on the cold side and moisture from the balance of the bin will condense on the cooler grain, and possibly cause heating. A carload of cold grain stored in a mass of warm grain will rise in moisture content and heating is likely to result. All of these translocations are obviously dependent on the movement of moisture-laden air.

Temperature levels also affect the storage quality of grain. In the United States, Argentina, and Australia, grain brought to the terminal elevator by car or truck is likely to enter storage at temperatures well above 85°F., and warm weather may prevent effective natural cooling for 2 to 4 months. In fact, repeated exposure to low temperatures is required to cool it substantially. The 2-minute exposure to cold air experienced by grain during transfer from one bin to another, plus the effect of exchanging its original warm atmosphere for a new one of cold air, is only sufficient to reduce its temperature by 6 or 7 degrees in the coldest weather. Repeated transfers are necessary for effective cooling, though other methods, such as "cold-blasting," or running the grain through a dryer using air at outside temperatures, may bring its temperature down to within a few degrees of the outside air. The temperature of grain 2 or 3 ft. from a bin wall is little affected by radiation or conductance (19). However, since about one-third of the volume of a grain mass is occupied by air, convection currents tend to equalize grain and outside temperatures. The rate at which this occurs is a function

of the temperature differential.

There is no completely safe temperature level for grain storage. Grain may start heating from any point, though, in general, lower temperatures are safer. Most molds and bacteria that play a part in grain deterioration grow slowly or not at all below 70°F. Insects are seldom very active below 60°F. (2). Germ discolorations, such as "sick damage" in wheat or rye, "blue eyes" or "rancid germ" in corn, "heat damage" in barley or oats, occur very slowly or not at all below 70°F. On the other hand, higher temperatures do not always mean that any of these forms of damage will appear, as instances are known of long-term storage at temperatures above 100°F. without damage. In Argentina and Brazil, large quantities of grain are commonly stored at such temperatures.

Higher temperatures are, however, a definite encouragement to insects, and all cereal grains contain some insects. Some infestation occurs in the field, either before or after harvest, and more is picked up on the way to market, from bags, from wagon boxes, from the legs and bins of the country elevators, from boxcars, and finally from the handling equipment of the terminal elevator itself. The terminal operator must be continually suspicious of insect activities. If grain temperatures are below 60°F. he may feel relatively safe, but the higher the temperature, the faster the insects will multiply and the sooner they will appear in damaging numbers.

The insects most feared by the warehouseman are the weevils. These are of two varieties, the granary weevil and the rice weevil, both of which destroy the grain kernels, first the ones in which they hatch, and later adjacent kernels. The granary weevil, *Sitophilus granarius* (L.), is larger and darker, and cannot fly, so is only found in elevators or in grain conveyances, while the rice weevil, *Sitophilus oryza* (L.), can fly, and so can infest grain in the field. The terminal superintendent, not recognizing the individual species, is likely to include all other insects found in the grain under the term "bran bugs," since all but one of them, the lesser grain borer, *Rhizopertha dominica* (F.), are dust-eaters and do not directly damage the kernel. Whether the pest is a weevil or a bran bug, however, its presence in substantial numbers is always evidenced by a rise in temperature. At first the rise may be only a few degrees a week for a few weeks, but then the temperature of the entire bin is likely to rise 20°F. in a few days. The bran bugs cause more serious heating than do the weevils, apparently because the weevils tend to scatter, while the smaller insects tend to bunch up into pockets, bringing about more rapid though more localized heating. Fortunately, neither will carry the grain temperature much beyond 106°F. as the

insects apparently move out, die, or fail to multiply above that temperature. Often, however, their activities are sufficient to cause serious damage to the grain and they may set off heating from other causes which will do still further damage.

Other grain pests seldom cause serious trouble in a terminal. Two varieties of moth, the Angoumois, *Sitotroga cerealella* (Oliv.), and the Indian-meal moth, *Plodia interpunctella* (Hbn.), sometimes appear on the surface of stored grain where their larvae form webs. Sometimes the larvae gouge out the germs of the grain, and sometimes the grain just under the web sweats and begins to heat, but the damage is confined to the surface layers, and, of course, the moths cannot multiply beneath the surface. Tyroglyphid grain mites are sometimes the cause of heating, but are usually near the surface, or sometimes where an old surface has been buried under new grain.

While the onset of deterioration caused by insects and by most microorganisms is signaled by a rise in temperature, this is not usually true of at least two other forms of damage. These are the so-called "blue mold" damage in corn (4, 13, 18, 22) and "sick damage" in wheat or rye (5, 16, 19).

Increases in blue-mold damage to corn stored in a terminal elevator usually, but not always, take place in artificially dried corn. In dried corn, the first visible sign is a discolored thread across the center of the germ, apparently where drying has cracked the skin. Where the mold is exposed on the surface, it is white, but when it begins to spread it does so under the bran coat and the germ becomes blue. Often it will continue to spread underneath the entire branny layer and eventually cause the whole kernel to turn black. In natural corn it spreads under the bran covering the germ, starting at the top, but seldom covers the rest of the kernel, and when it does, its progress is much slower than in artificially dried grain. Not all corn crops are subject to this form of damage; some show only occasional traces, and others none at all. The mold apparently does not increase at temperatures under 65°F. If it raises grain temperature at all, it does so very slowly, and causes only a faint or doubtful musty odor.

The second form of damage that may take place without heating and about which little is known is sick damage. It occurs most often in soft red winter wheat, but also in white and hard winter wheats, in rye and barley, and has even been detected in spring wheat. Sometimes it will appear in a matter of weeks; at others, under similar conditions, it cannot be found after many months of storage. Sometimes grain at 13% moisture is damaged severely, while again grain with 15% moisture may escape. Sometimes it seems to occur in grain from certain growing

areas, at others it is found at certain locations regardless of the origin of the grain. It can occur at fairly low temperatures and does not necessarily appear at high temperatures, though when it does its progress is much more rapid. While sick damage may be found in heating grain and may be associated with musty odors, it is often found in grain that has not heated or become musty. It would appear that moisture content, temperature, and time are all involved in bringing about this form of damage, and that some factors at present unknown must also play a part. Undoubtedly, the higher temperatures and higher moistures of grain arriving at terminals, as a result of present-day quick-harvesting methods, aggravate the problem.

Sick damage consists principally of a darkening of the embryo. A creamy or yellowish color appears first, then it turns brown and eventually black. By that time the balance of the kernel often has a grayish or dead appearance, though sometimes it may appear slightly pinkish, or perfectly healthy. Viability is always reduced. While there has not been an adequate investigation of the effect of sick damage on the milling or baking qualities of wheat, it is often claimed that yield, loaf texture, and loaf volume are all impaired to some extent.

We have discussed the principal sources of danger to grain condition and must now ask how the prudent warehouseman avoids losses arising from these sources. How is a dangerous situation detected, and when found what action is taken?

Unfortunately, only three methods of anticipating condition troubles are yet known, and none is as reliable as might be wished. They are based on temperature reading, visual inspection, and experience.

Grain stored in masses has very low conductivity, so that outside temperature variations affect the grain temperatures little if at all. Any temperature changes that take place within the mass, unless they are very slow and small, must therefore be presumed to arise from some activity on or within the grain kernels themselves, and to constitute warning of damage to follow if the cause is not found and corrected. Methods of reading temperatures in stored grain have already been described. It has also been noted, however, that damage can occur without any rise in temperature. So, while temperature readings are of great assistance, they do not provide complete assurance that all is well.

Many operators will not trust temperature records at all and depend almost entirely on visual inspection. This begins when the grain is entering the elevator. It is then carefully examined for moisture content, dockage, damage, insects, and any other evidence of its quality or past behavior. After the grain is in storage, a transferring schedule is set up depending on the quality of the grain, its temperature, and the

operator's past experience with the same type of grain. At each transfer it is sampled, and these samples are carefully examined for any change in any factor. If no changes are found the superintendent can only be sure that nothing has happened yet and wait for the next scheduled turn. Between transfers the surface of the stored grain is inspected at regular intervals for any visible evidence of change in condition, or samples drawn from the bin by probing, or by momentarily opening the draw-off gate, are inspected.

Experience is a very expensive teacher in the grain trade, since a few sad experiences with grain condition losses may end the warehouseman's career. Further, it is not entirely reliable since no two crops behave alike or present the same problems. Without it, however, the supervising of terminal operations becomes much more difficult. While much of what experience teaches has already been noted, a few general rules of conduct drawn from its many lessons will be given.

The risks of losses during storage are reduced if the grain is cool, if it is low in moisture, if it has not been artificially dried, if it has not heated, if it is high in grade, clean and free from broken kernels, if it is not infested, and if it has already gone through the "sweat." To the extent that grain does not possess these qualities, the risks of its suffering loss of condition are increased. If the temperature of the grain is high it should be reduced as soon as possible. If high-moisture grain must be accepted, it should be moved into consumption as soon as possible, or artificially dried, or mixed off with low-moisture grain. Of two mixtures having the same final moisture content, that in which the average moisture level has been reduced by means of a small quantity of very dry grain will not keep as well as that in which a larger quantity of grain that is not so low in moisture has been used to accomplish the purpose. Finally it should be said that no matter what its temperature and moisture content no lot of grain should be regarded as entirely safe from loss of condition over a long storage period.

When the terminal operator has evidence of condition problems in the form of temperature increases or changes in visual appearance, what can he do to preserve his grain? The usual course is first to find out the cause of the trouble and then to take the proper preventive steps.

If he finds insects present he may fumigate. Indeed, many warehousemen will fumigate on arrival all grain showing evidence that a serious infestation might develop during storage. Several kinds of fumigants are on the market, all very effective if used properly. Those most widely used at present consist of mixtures of carbon tetrachloride with one or more of the following substances: ethylene dichloride, ethylene dibromide, and carbon bisulfide. Such mixtures are usually poured into the bin

at regular intervals as it is being filled. Calcium cyanide is also used; the powder is fed from an apparatus into the grain stream as it enters the bin. In the bin, it decomposes to produce hydrocyanic acid gas, which is lethal to all living organisms. Another commonly used fumigant is chloropicrin. This liquid is also applied to the grain as it flows into the bin; it vaporizes to form a heavy gas. Since some fumigants are deadly poisons, and all are unpleasant if not dangerous, fumigation should be carried out only by trained operators supplied with suitable gas masks.

If the grain is heating from other causes, it must be cooled. If discovered in its early stages, heating may be stopped or slowed sufficiently by one or more ordinary transfers, or by dropping the grain down the loading spout and through the open air into the unloading pit from which it is re-elevated, or by running it through the grain dryer through which unheated air is passed. If the heating is localized in one spot, and does not affect the entire bin, an effort is usually made to separate the heating grain for special attention. These procedures may be effective, particularly if temperatures are reduced below 60°F., but quite often they fail and then the grain must be dried. If drying also fails, there is no alternative but to dispose of the grain.

If sick damage or blue mold is found to be increasing and if outside temperatures are not below 60°F., transferring and handling the grain are usually ineffective. In fact, they sometimes appear to aggravate the trouble. Drying is the only remedy, and in some cases even that will not put an end to the deterioration unless it is carried to a point which cannot be justified by economic considerations.

Accidents. The most spectacular accident that can happen to a terminal elevator is a dust explosion. Wherever cereal grains are handled, a cloud of gray dust fills the air. This dust consists chiefly of fine particles rubbed off the kernels. It is combustible and capable of forming highly explosive mixtures with air. A dust explosion can shatter a concrete bin wall from top to bottom, scatter a concrete headhouse over several blocks, and even lift bins of grain weighing hundreds of tons. While modern technics have made dust explosions comparatively rare, in the past they sometimes caused immense damage (Fig. 7) and considerable loss of life.

One of the most severe was the explosion in 1878 which shattered the Washburn-Crosby flour-mill warehouse in Minneapolis. Another occurred in Chicago in 1921 in the Armour elevator, then the largest and most modern terminal elevator in existence. Portions of the structure were entirely destroyed, and blocks of concrete weighing over a ton were thrown 200 yards away. Twenty or more serious elevator ex-

Fig. 7. Results of a disastrous dust explosion that occurred in 1921.

plosions have been reported from different parts of the world since then and this hazard must still be reckoned with in terminal elevator operation.

There is no doubt that these tremendous explosions are caused by the combustion of grain dust suspended in the air. They have been reproduced on a miniature scale in the laboratory, and the conditions under which they occur have been studied (8, 20). Three things are required: a suitable mixture of dust and air, a spark, and a confined area.

Since dust is present in the air wherever grain is handled, it may seem remarkable that explosions are so rare. One reason is that a mixture of dust and air must meet a number of requirements before it becomes dangerously explosive. Elevator men report seeing actual flames in elevators while the air was thick with dust, yet no explosion followed. In earlier years, oil lanterns were used to light the elevators at night, and were often suspended from ropes and lowered into dusty bins to measure depth of the grain, without serious mishap. The reason that disaster does not always follow the introduction of a flame into a dusty atmosphere is that heavy particles of dust, especially in turbulent air, are difficult to ignite. The hazard is greatest when the dry dust particles are fine and the air quiescent, which explains the tendency for explosions

to occur soon after the plant has been shut down, when only fine dust particles remain suspended in the quiet air.

The spark or flame that initiates an explosion may be produced in many ways. It may be caused by a nail in a shoe, the edge of a shovel on the floor, a defective motor or switch, defective wiring, static electricity, a hot bearing, a careless cigarette, a broken light—any of these is sufficient. There are often two stages in a dust explosion. Upon the ignition of the explosive mixture there is a flash of flame accompanied by a gust of air which lifts fine dust lodged on walls and other surfaces. The dust cloud thus created immediately ignites to cause a second and much more powerful explosion. In an unrestricted area, the air pressure caused by the sudden rise in temperature is dissipated as a rapidly moving pressure wave. But in the basement of the elevator, in the tunnels under the bins, or up in the headhouse, the pressure builds up in a fraction of a second and may be sufficiently great to shatter the strongest barriers.

With a knowledge of how explosions are caused, the means for preventing them become obvious. First, dust must be removed from the elevator. Second, care must be taken to avoid causing sparks or flame. Third, the structure must be built in such a way as to permit quick dissipation of the pressure if a flash should occur. All these have been done, and with good results. While there is bound to be dust in the air around any grain-handling operation, it is not sufficient to sustain an explosion if there is no supplementary supply of dust nearby on floor, walls, ceilings, ledges, or machinery. The primary requirement, then, is that the elevator be kept clean by frequent sweeping and adequate dust-collection systems. To prevent sparks special types of dustproof motors, switches, and lights are available; equipment is grounded to prevent sparks of static electricity; men are required to wear shoes having no nails; and shovels often have edges sheathed in protective materials. Great pains are taken to avoid all other possible sources of a fatal spark. Modern construction designs provide against the final source of danger—a tightly enclosed space. The principal objective is to furnish plenty of venting area, through which an explosion may expend its energy without doing much damage. Where there were once solid walls, in such vulnerable locations as headhouses, tunnels, or galleries, windows are now found, and these are always loosely fastened or hinged to swing outward.

Much evidence is available on the effectiveness of these measures, and there can be no doubt that, if they are observed with care and vigilance, the terrible losses of life and property in explosions of the past will not be repeated in the future.

Other types of accidents may be grouped as originating in the machinery and tools used in the handling of grain, or in the grain itself. Possibly the equipment used in grain handling is no more dangerous than that used in other occupations, but working in grain elevators is much too near the top of the list of hazardous occupations. A continuous program of employee education on the danger of carelessness, on guarding of moving machinery, on safe practices and procedures, and the elimination of hazardous conditions, must be vigorously pursued in order to keep the accident rate at a minimum.

Accidents involving the grain itself are of two types. Men may accidentally become buried in the grain when they attempt to stand on the surface while the grain is being drawn; under these conditions, a man will immediately sink beneath the surface and be either smothered or crushed. Or, grain will sometimes cake and stand up along a bin wall until disturbed, when it will crumble and bury any man standing below it. Sometimes grain will arch entirely across a bin, so that the lower part of the grain will flow out and leave the upper part undisturbed until it caves in with the weight of a man on the surface.

The other serious type of accident originating with the grain itself is asphyxiation. Men have gone into bins nearly filled with grain and collapsed and died in a matter of minutes. The first thought is that the cause of death must be some poisonous gas originating in the grain, but this has not proved to be true. At least two cases were carefully studied and reported, and others have been commented upon (15, 21). In all cases the oxygen content of the air above the grain was too low to support life.

These fatal atmospheres apparently are caused by exhaustion of the oxygen from the air and its replacement with carbon dioxide as a result of respiration of grain and molds. This type of accident usually occurs over grain of high moisture, or grain that is out of condition and has been heating. All grain and its microflora respire to some extent, however, and an oxygen content as low as 4% has been found in sound grain with moisture content below 13% after storage in steel bins for long periods.

Another cause of fatal or near-fatal accidents is the use of fumigants, applied as liquids which quickly volatilize. The normal atmosphere is displaced by the resulting gases, and entrance to a bin before these toxic gases are dissipated may, even with the use of a gas mask, cause death.

The only sure way to avoid these accidents with grain is never to allow a man to enter any bin at any time unless he is wearing a harness or safety belt with a stout rope attached, and that kept in the hands of at least one other man outside the bin. In this way the man in the

bin can be removed immediately and safely if there are any signs that he is in distress.

Terminal Capacities

As the principal economic function of the terminal elevator is to store large quantities of grain, these plants have had their greatest development in the major surplus grain-producing areas, namely, the United States and Canada. The number of terminal elevators and the

TABLE II

STORAGE AT PRINCIPAL MARKETS IN THE UNITED STATES

Market	No. of Elevators	Capacity
		Bu.
Seattle, Washington	8	6,725,000
		1,230,000*
Tacoma, Washington	4	466,000
		2,210,000*
Portland, Oregon	15	246,300
San Francisco, California	17	9,800,000*
	1	2,250,000
Minneapolis–St. Paul, Minnesota	69	93,224,000
Duluth, Minnesota; Superior, Wisconsin	23	54,975,000
Milwaukee, Wisconsin	20	40,170,000
Chicago, Illinois	35	53,664,000
Detroit, Michigan	6	2,600,000
Toledo, Ohio	15	14,739,000
Cleveland, Ohio	6	895,000
Buffalo, New York	35	53,808,000
Omaha, Nebraska	20	28,885,000
Hutchinson, Kansas	14	22,070,000
Wichita, Kansas	13	24,830,000
St. Joseph, Missouri	12	10,977,000
Kansas City, Missouri	33	62,897,000
St. Louis, Missouri	36	23,850,000
Indianapolis, Indiana	8	10,050,000
Evansville, Indiana	5	2,075,000
Cincinnati, Ohio	9	6,160,000
Enid, Oklahoma	13	43,389,000
Memphis, Tennessee	9	4,000,000
Nashville, Tennessee	14	2,538,400
Fort Worth, Texas	13	27,800,000
Houston, Texas	1	5,000,000
Galveston, Texas	3	7,365,000
Port Arthur, Texas	1	500,000
New Orleans, Louisiana	2	2,872,000
Boston, Massachusetts	3	2,500,000
Albany, New York	1	13,500,000
New York, New York	3	4,450,000
Philadelphia, Pennsylvania	4	5,565,000
Baltimore, Maryland	5	12,750,000
Norfolk, Virginia	2	750,000
Total	478	661,775,700

*Capacity in bushels for sacked grain.

TABLE III

CANADIAN TERMINAL ELEVATORS

Area	Public and Semipublic		Mill and Private	
	Number	Capacity	Number	Capacity
		Bu.		*Bu.*
Pacific coast	10	21,756,500	11	1,170,110
Prairies	6	18,100,000	29	16,835,000
Hudson's Bay	1	2,500,000	..	....
Lakehead	24	89,517,200	6	2,685,000
Georgian Bay area	8	26,916,000	..	....
Lower Lake area	3	9,000,000	5	10,175,000
St. Lawrence River	9	32,012,000	1	750,000
Atlantic coast	4	5,276,800	..	....
Total	65	205,078,500	52	31,615,110

total storage capacity at each of the principal grain markets in the United States are shown in Table II. The number and capacity of the terminal elevators in different parts of Canada are given in Table III.

These tables show that the largest storage market in the United States is the Minneapolis-St. Paul area in Minnesota, with 93,000,000 bu. It is equaled in Canada by the Fort William-Port Arthur area at the head of the Great Lakes in Canada. Since the general movement of grain is eastward toward areas of consumption, there is a tendency in both countries to develop large quantities of storage space at markets in the path of this annual flow of grain.

A terminal elevator may have a storage capacity anywhere between 500,000 bu. and 15,000,000 bu. The average capacity of the elevators listed in Table II is about 1,370,000 bu. The average capacity of the Canadian terminals listed in Table III is 1,426,000 bu.

At each market the total storage capacity is divided between warehousemen and processors. The proportion varies with each market, but the grain storage capacity of processors such as flour millers, feed manufacturers, maltsters, and distillers tends to increase in the eastern areas. For instance, in Kansas City, Missouri, the space is divided into 34,480,000 bu. operated by warehousemen and 28,417,000 bu. operated by processors. In Buffalo, New York, the space is divided into 19,400,000 bu. operated by warehousemen and 34,408,000 bu. operated by processors.

In the United States, the recent trend in the location of new grain storage has been toward the producing areas. This has been encouraged by the policy of the Commodity Credit Corporation in erecting or obtaining temporary facilities near the producer, by inadequate transportation facilities such as shortage of boxcars, and by the increased volume

TABLE IV

ESTIMATED CAPACITY OF OFF-FARM COMMERCIAL AND CCC STORAGE FACILITIES IN THE UNITED STATES

State	Type of Storage		Total Commercial Capacity	CCC-Owned Bins	
	Bulk	Sack or Not Identified		Number of Bins	Storage Capacity
	Bu.	*Bu.*	*Bu.*		*Bu.*
Alabama	2,686,000	1,939,000	4,625,000	100	325,000
Arizona	5,710,000	1,740,000	7,450,000	....	....
Arkansas	26,996,000	1,954,000	28,950,000	2	246,000
California	47,425,000	68,809,000	116,234,000	300	975,000
Colorado	31,191,000	4,827,000	36,018,000	1,025	4,252,750
Connecticut	307,000	229,000	536,000	....	....
Delaware	1,326,000	108,000	1,434,000	40	130,000
Florida	705,000	4,750,000	5,455,000	....	....
Georgia	5,663,000	6,545,000	12,208,000	1	1,000
Idaho	28,210,000	11,573,000	39,783,000	....	....
Illinois	198,931,000	2,434,000	201,365,000	30,132	107,151,916
Indiana	48,565,000	393,000	48,958,000	7,232	26,616,545
Iowa	89,644,000	1,085,000	90,729,000	38,830	168,972,579
Kansas	205,823,000	1,125,000	206,948,000	4,698	18,533,060
Kentucky	12,383,000	5,213,000	17,596,000	740	2,464,980
Louisiana	10,854,000	25,707,000	36,561,000	16	8,733
Maine	1,980,000	45,000	2,025,000	....	....
Maryland	14,676,000	271,000	14,947,000	1	1,250
Massachusetts	3,551,000	894,000	4,445,000	....	....
Michigan	17,921,000	4,912,000	22,833,000	1	8,960
Minnesota	190,543,000	546,000	191,089,000	8,510	42,810,907
Mississippi	4,857,000	3,390,000	8,247,000	....	....
Missouri	88,009,000	2,600,000	90,609,000	3,204	13,972,636
Montana	29,845,000	811,000	30,656,000	230	747,500
Nebraska	68,127,000	930,000	69,057,000	10,458	80,946,757
Nevada	176,000	408,000	584,000	....	....
New Hampshire	369,000	600,000	969,000	....	....
New Jersey	7,616,000	712,000	8,328,000	15	48,750
New Mexico	7,768,000	1,644,000	9,412,000	195	1,332,750
New York	79,558,000	4,887,000	84,445,000	....	....
North Carolina	7,542,000	2,748,000	10,290,000	104	334,000
North Dakota	63,476,000	....	63,476,000	3,085	10,226,400
Ohio	61,927,000	14,587,000	76,514,000	4,610	15,362,415
Oklahoma	95,013,000	1,144,000	96,157,000	3	114,600
Oregon	36,376,000	12,411,000	48,787,000	...	...
Pennsylvania	18,176,000	2,933,000	21,109,000	181	556,250
Rhode Island	41,000	97,000	138,000	....	....
South Carolina	2,143,000	857,000	3,000,000	125	406,250
South Dakota	27,551,000	....	27,551,000	8,547	40,972,766
Tennessee	13,152,000	3,030,000	16,182,000	10	176,000
Texas	196,181,000	21,300,000	217,481,000	649	5,416,716
Utah	12,697,000	2,531,000	15,228,000	....	....
Vermont	825,000	1,106,000	1,931,000	....	....
Virginia	5,000,000	3,350,000	8,350,000	93	295,000
Washington	81,963,000	8,711,000	90,674,000	....	....
West Virginia	558,000	176,000	734,000	....	....
Wisconsin	79,535,000	2,228,000	81,763,000	536	1,377,900
Wyoming	2,440,000	1,641,000	4,081,000	....	....
Total	1,936,011,000	239,931,000	2,175,942,000	123,673	544,785,370

of grain going into animal feeds near the producing areas.

A recent news release by the Production and Marketing Administration of the United States Department of Agriculture gave a tentative listing of storage space off the farm in the United States; this is reproduced in Table IV.

Total production of the eight major grains grown in the United States in 1950 was reported by the Department of Agriculture to have been 6,087,810,000 bushels. This was a little above the average, yet almost half that production could be accommodated in the off-farm storage space listed in Table IV. Farm storage has been estimated at two and a quarter billion bushels (Northwestern Miller, Feb. 14, 1950). If we add this to the off-farm storage (Table IV), we arrive at a grand total of close to five billion bushels, enough to accommodate about 80% of the average annual grain production.

In spite of these vast storage facilities, all grain everywhere in the United States cannot always be properly housed. Economic factors make it reasonable to provide any area with only enough storage for an average crop served by normal transportation facilities. If a crop in a certain area is much greater than average, some of it must generally be piled in the open. Even under average conditions, grain must move steadily to terminal elevators and to processing industries, if congestion is to be avoided in country elevators and on the farm. Hence, any reduction in rail and other transportation facilities, such as may occur during a war or other crisis, may overtax normal storage. Again, if markets are not available for surplus crops, the terminals themselves may become choked and hold back the flow of grain until too much must be held on the farms. Under these conditions, whether or not additional temporary storage will be built depends on the economics of the total situation. Thus every case of inadequate storage facilities demands separate study, and no general solutions can be offered.

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Drying of Grain

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The amount of moisture contained in grain has a definite effect on its suitability for ordinary processes such as harvesting, storing, feeding, germinating, and milling of various kinds. For many processes there is an optimum or critical moisture content above or below which the results are not satisfactory. While grain is growing, the moisture content is high. As it ripens the percentage of moisture decreases, and moisture normally continues to leave the kernels after ripening until they are what we call "dry." In this condition, however, grain still contains water in amounts that may be surprising. A bushel of "dry" wheat, for example, is likely to contain from ½ to 1 gal. of water (7 to 15 lb. per 100 lb.).

For most purposes it would not be desirable to free the grain completely from water even if it were convenient to do so. Perhaps the most important practical reason for concern about the moisture content of grain is that molds, yeasts, and other microorganisms require moisture for their growth (see Chapters III and IV). They do not get the necessary moisture unless the grain contains a relatively high percentage of water. The minimum moisture content of grain above which microorganisms may cause damage is within the range of roughly 10 to 15%; the exact level depends upon the kind of grain, the temperature, and the nature of the organism.

The discussion of grain drying which follows is divided into three sections: general considerations, theoretical considerations, and practical considerations. The treatment of theoretical considerations is necessarily somewhat technical, and some readers may not wish to follow the development in detail. For this reason, an attempt has been made to keep each section as independent as possible of the others.

General Considerations

The drying of grains is similar to air drying of other solid materials. However, many other materials that are dried, such as fresh fruits and

vegetables, contain much more water. General discussions of drying wet materials (10, 26, 47, 48, 60, 74) indicate that, in the normal range of moisture in grains, the rate of drying is limited by resistance to moisture flow within the kernel to a greater extent than by the resistance to vapor flow from the surface. When drying grains we are usually concerned with removal of a limited amount of moisture. In practice, grain does not need to be dried from initial moistures higher than perhaps 35% nor below about 10% (wet basis), and this discussion will be confined to this practical range of moisture.

Methods of Reporting Moisture Content. The amount of moisture in grain is usually expressed in per cent by weight. A given percentage of moisture by weight, however, may have either of two meanings. For example, if we are told that grain has a moisture content of 25%, we might expect this to mean that 100 lb. of grain contains 25 lb. of water; this is right if the moisture content is expressed in per cent *wet basis.* On the other hand, it is just as reasonable to assume that the 25% moisture content is expressed on a *dry basis;* in this case 100 lb. of grain contains 20 lb. of water and 80 lb. of dry matter since 20 is 25% of 80. Accordingly, when the moisture content is reported as percentage it is necessary to have an understanding as to which basis is used. One is neither more correct nor more logical than the other. For some purposes it is more convenient to use the wet basis; for others, dry basis. In the United States, particularly for commercial purposes, it is customary to express grain moisture content in per cent wet basis, and in the Federal Grain Standards the wet basis is used.

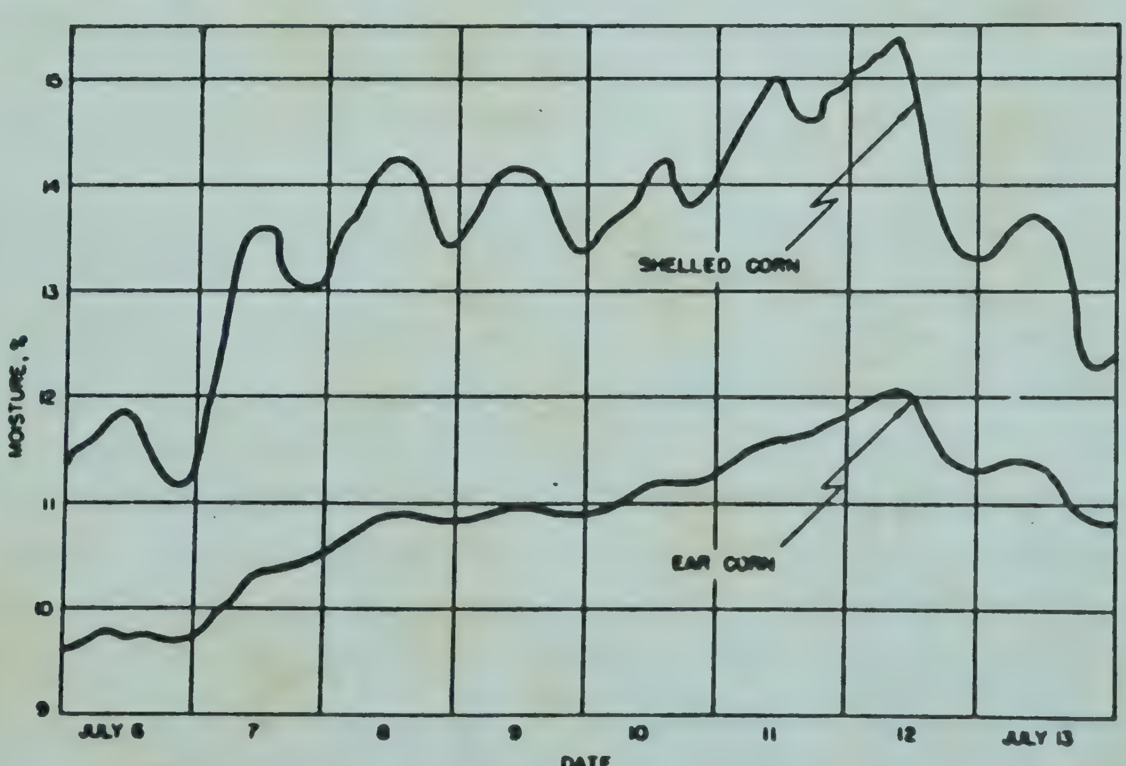

Fig. 1. Typical continuous changes in moisture content (wet basis) of shelled corn and ear corn completely exposed to the atmosphere (Hukill, 27).

Grain-Air Equilibrium. Grain is hygroscopic and holds an appreciable amount of water even after long exposure to relatively dry air. If the relative humidity of the air is increased, the grain will then absorb moisture. Accordingly, grain that is exposed in thin layers to air with fluctuating humidity absorbs and gives off moisture, tending at all times to reach equilibrium with the air. Figure 1 illustrates typical changes in moisture content in shelled corn and ear corn exposed to changes in atmospheric humidity, but protected from rain.

While the relative humidity of the air is not shown in this figure, on typical days the humidity is low in the afternoon and high in the early morning. During the periods of low humidity the grain dries and when the humidity is high it picks up moisture. For this reason the moisture is usually highest around noon and lowest shortly before midnight; the moisture content curve follows the relative humidity roughly, but the peaks lag several hours behind. The shelled corn follows the humidity changes more closely than does the ear corn.

Experiments have shown that for each kind of grain there is a definite relation between grain moisture content and relative humidity of the air with which the grain is in moisture equilibrium. That is, for any given percentage of moisture in the grain, there is a definite relative humidity of air to which the grain might be exposed without losing or gaining moisture. The grain moisture content which is in equilibrium with a given relative humidity is frequently called the "equilibrium moisture content" for that humidity. The equilibrium moisture content for a given relative humidity changes slightly as the air temperature changes. Equilibrium moisture contents for several of the grains at various humidities at 77°F. are shown in Table I. At higher temperatures, the moisture content for each humidity will be lower than that shown (12, 18, 19, 43).

Drying of Fully Exposed Grain. Grain and air are in equilibrium when the vapor pressure of the moisture in the grain is equal to that in the air; the flow of moisture to or from the grain is zero and its moisture content remains the same. When the moisture content is higher than the equilibrium value, moisture flows from the grain, drying it (3, 4). The rate at which the moisture leaves the grain depends upon how much the grain is out of equilibrium with the air surrounding it, on the temperature, and on the nature, size, and shape of the kernels.

Various experimenters have measured the rates of drying of various grains exposed to constant conditions of air temperature and humidity. A typical drying curve is shown in Figure 2. In this case a sample of oats in a layer only one kernel deep was exposed to air having a temperature of 129.5°F. and a relative humidity of 30.3%. The grain was

TABLE I

MOISTURE CONTENTS IN EQUILIBRIUM WITH AIR OF VARIOUS HUMIDITIES AT ROOM TEMPERATURE (APPROXIMATELY 77°F.)

	Moisture Content (Wet Basis)							Authority
	15% R.H.	30% R.H.	45% R.H.	60% R.H.	75% R.H.	90% R.H.	100% R.H.	
Barley	6.1	8.5	10.0	12.1	14.4	19.5	26.8	C & F[a]
Buckwheat	6.7	9.1	10.9	12.7	15.0	19.1	24.5	C & F
Shelled corn, YD	6.4	8.4	10.5	12.9	14.8	19.1	23.8	C & F
Shelled corn, WD	6.6	8.5	10.4	12.9	14.7	18.9	24.6	C & F
Shelled corn, pop	6.8	8.5	9.8	12.2	13.6	18.4	23.0	C & F
Flaxseed	4.5	5.6	6.3	7.9	10.0	15.2	21.4	C & F
Oats	5.7	8.1	9.6	11.8	13.8	18.5	24.1	C & F
Rice, milled	6.8	9.0	10.7	12.6	14.4	18.1	23.6	C & F
Rye	7.0	8.7	10.5	12.2	14.8	20.6	26.7	C & F
Sorghum	6.5	8.6	10.5	12.0	15.3	18.8	21.9	C, R, & F[b]
Soybeans	....	6.2	7.4	9.7	13.2	....	....	R & G[c]
Wheat, white	6.8	8.6	9.9	11.8	15.0	19.7	26.3	C & F
Wheat, durum	6.6	8.5	10.1	11.5	14.1	19.3	26.7	C & F
Wheat, soft red winter	6.3	8.6	10.6	11.9	14.6	19.7	25.6	C & F
Wheat, hard red winter	6.4	8.5	10.5	12.5	14.6	20.1	25.4	C & F
Wheat, hard red spring	6.8	8.5	10.1	11.8	14.8	19.7	25.0	C & F

[a] Coleman and Fellows (11a). Moisture content determined by water-oven method.

[b] Coleman, Rothgeb, and Fellows (11b). Moisture determined by official air-oven method.

[c] Ramstad and Geddes (53a). Moisture determined by vacuum-oven method. Values in above table interpolated from published graph.

weighed periodically and the moisture content computed to a dry basis. As is characteristic of experiments on rates of drying, the moisture content dropped off rapidly at first, then more and more slowly. At the end of the experiment, when the moisture content was almost at equilibrium with the air, the drying was so slow that it could hardly be detected by the change in weight.

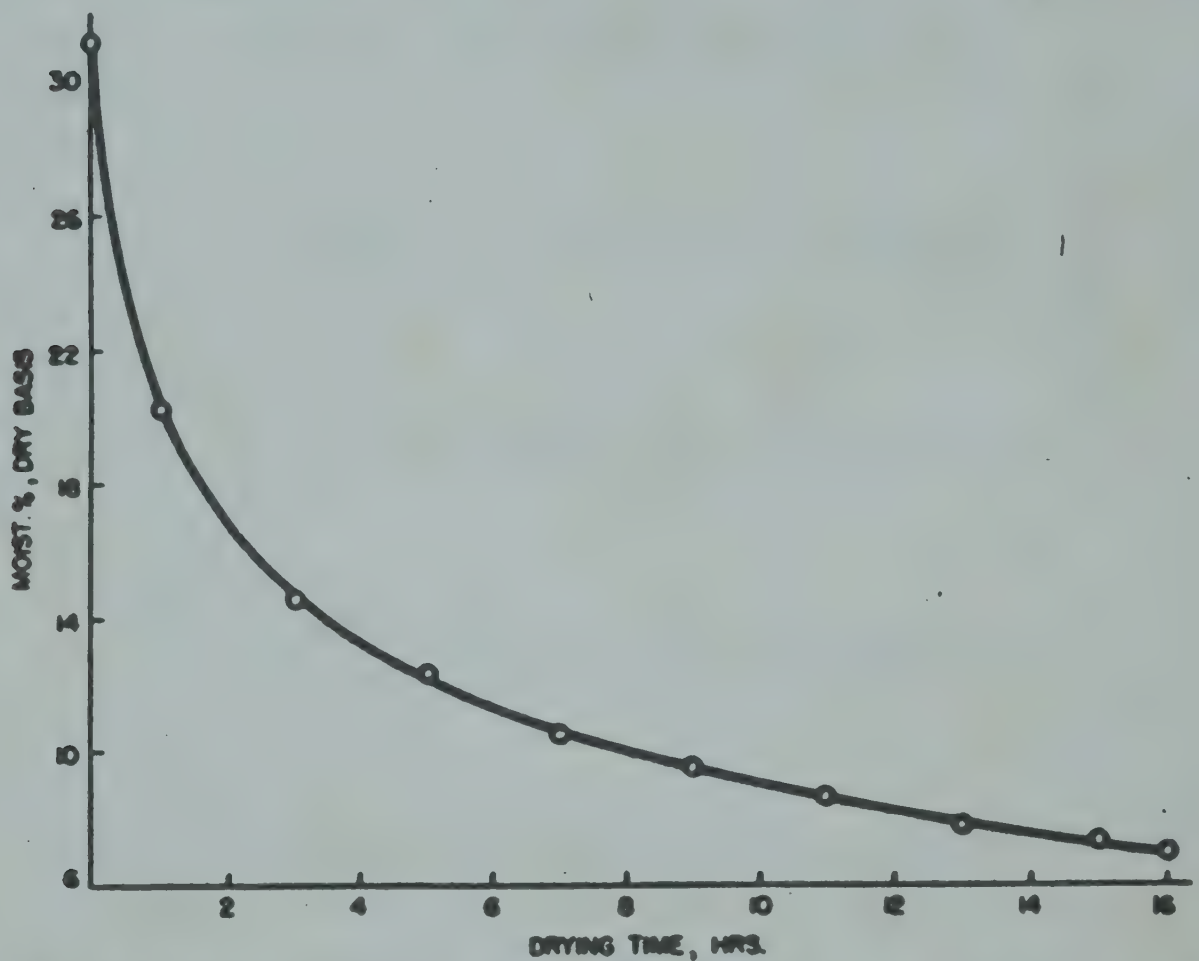

Fig. 2. Moisture content of a fully exposed oat sample in an air stream having a constant temperature and relative humidity (Holman, 24).

This description applies to the drying of grain of any kind that is fully exposed to an atmosphere of constant temperature and humidity. In general, the rate of drying is faster if the initial moisture content is high, if the temperature is high, or if the humidity is low. With very slow air movement, increasing the air velocity also causes faster drying; under other conditions the effect of air velocity change is negligible. The individual effects of each of these variables combine to cause the grain to dry in a particular manner such as, for example, that for the oat experiment that was illustrated in Figure 2. However, the way in which each of the above variables affects the rate of drying of fully exposed samples has not been worked out completely enough for accurate prediction of the exact rate of drying under any given set of conditions.

Figure 2 showed that the rate of drying drops off as the moisture content goes down. The data of the experiment may be examined to see

if the rate of drying at each moment is proportional to the amount of moisture yet to be removed at that time. The simplest test is to make a semilogarithmic plot of the data. If the points fall on a straight line in such a plot, then the rate of drying at all times is proportional to the amount of moisture yet to be removed, and a simple formula expresses the relation of the moisture content to the time of exposure. Data from

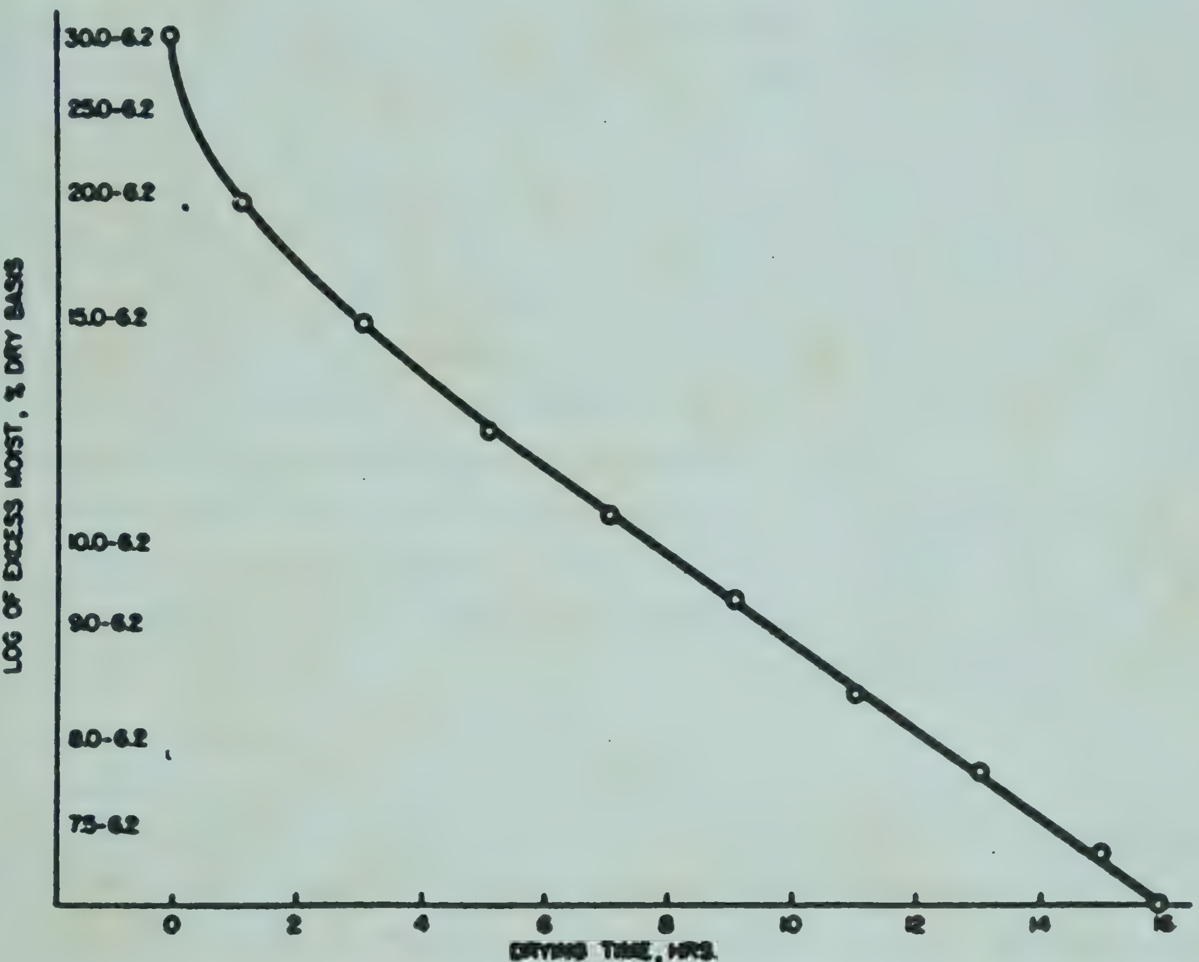

Fig. 3. Semilogarithmic plot of same data as shown in Figure 2.

Figure 2 have been plotted in this way in Figure 3. Time in hours is represented as before; but in this case the equilibrium moisture content is first subtracted from the observed moisture, and the logarithm of the percentage of moisture remaining to be removed is then plotted on the ordinate. The moisture content for these plots is expressed as percentage dry basis; for this purpose, percentage wet basis will not do.

The semilogarithmic plot of these data is not a straight line. If it had been, then the relation between moisture content and time could have been expressed by the formula,

$$M - M_E = \Delta Me^{-Kt} \qquad (1)$$

where: M is the moisture at any time; M_E the equilibrium moisture content; ΔM is the original moisture (M_0) minus M_E (all moisture contents expressed in per cent dry basis); e is the base of natural logarithms; K is a constant which expresses the slope of the plotted line; and t is time in hours. Under some conditions, observed drying rates are such

that the data do plot approximately as a straight line. The slope of the line K can then be used to express the characteristic drying rate of the particular kind of grain observed under the particular conditions of exposure. Sherwood (60) discusses the relation between moisture content and time for drying of solids in general, and suggests a modification of the above equation that might be used to describe certain cases of drying. Newman (47, 48) shows other modifications that might be applied to materials with particles of various shapes.

If changing the temperature and running a new experiment yields a different value of K, and if the observed values of K have a definite relation to the temperature, then a drying formula can be written with the effect of temperature included. Similarly, if the effect of various initial moisture contents, relative humidities, and air velocities could be included, a complete formula for predicting the rate of drying of exposed samples could be written. While the above equation (Eq. 1) describes the rate of drying only approximately, and under some conditions the approximation is poor, nevertheless, no other algebraic expression has been demonstrated to have general application.

Recently two separate experimenters (24, 51) have analyzed their results by using the equation,

$$M - M_E = \Delta Me^{-K_2t^n} \tag{2}$$

With the limited data reported, values of K_2 and n could be found such that the drying curve for all the cases observed could be described. In each case n is less than 1, and varies from about 0.55 to 0.85 in the tests reported. It remains to be determined whether this formula has general application to all drying conditions. If it does, then we may expect that values of K_2 and n for various grains, and equations for the effects of temperature, humidity, and air velocity upon these constants, will be forthcoming.

The drying rate is increased by higher temperatures. The change in the drying rate K with humidity might also be expressed as a function of the wet and dry bulb temperatures. As an approximation to the effect of changing humidity upon K, it has been suggested (28) that, at a given wet bulb temperature, K is proportional to the difference between the dry bulb temperature and the temperature at which the grain moisture would be in equilibrium with the air at the given wet bulb temperature. For very wet grain, having a relative humidity equilibrium of 100%, this would be the difference between the dry and wet bulb temperatures of the air; for drier grain the difference would be less.

Drying of Grain in Bulk. The foregoing discussion has been confined to rates of drying of fully exposed samples. That is, the grain is exposed

in such a way that each kernel is continually in contact with air of the specified temperature and humidity. In practical drying procedure this is not generally true. Most experiments reported on grain drying rates have been concerned with practical application, so little of the drying rate data in the literature is useful in establishing the laws governing exposed drying rates. In practice, air at some constant initial temperature and humidity is passed through or over grain and picks up some moisture. It then moves past more grain, but is no longer in its initial condition, so that only the first kernels with which it comes in contact will dry at the maximum rate. The rate at which the rest of the grain will dry depends not only on the character of the grain and the initial condition of the air but also upon the amount of grain present and the volume of circulating air. Even in drying a large batch of grain, however, each kernel at any instant dries as though it were individually exposed, in spite of the fact that the air temperature and humidity in contact with it may be changing continually.

The rates at which the air temperature and humidity change, as the air progresses through a batch of grain, depend upon how fast moisture is being evaporated from the grain. Thus, all changes taking place in the bin—decrease in moisture content of the grain, increase in humidity of the air, decrease in temperature of the air—are controlled by the rate at which the moisture is leaving each kernel as an individually exposed element. For this reason, knowledge of the effect of grain moisture content, character of grain, temperature and humidity of air, and air velocity upon *fully exposed* drying rate is essential to an understanding of how drying may be expected to proceed in any process. It is unfortunate that a general formula accurately describing the exposed drying rate, into which each of the above variables would fit, has not been developed. The previous discussion of the various tentative formulas proposed by experimenters indicates that approximations are available. Until a more exact analysis of fully exposed drying rates is formulated, these approximations may be used to develop an understanding of the way in which drying may be expected to proceed in any bulk drying process. Inasmuch as the exposed drying rate is described only approximately, the bulk drying rate developed from it will also be an approximation.

A method of predicting bulk drying rates, based upon approximations to true exposed drying rates, has been described (28). The computed bulk drying rates predict the actual rates only approximately but closely enough for practical application. Figure 4 shows the approximate moisture content of successive layers of grain in a bin being dried as a batch. It applies to grain having a uniform initial moisture content, through

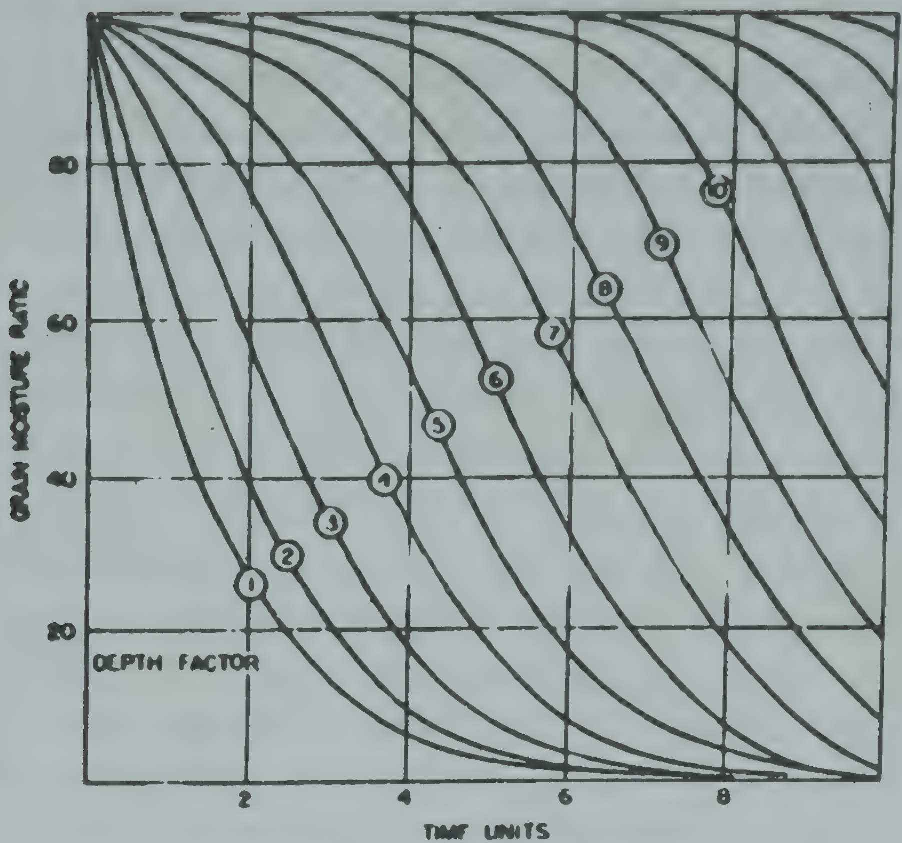

Fig. 4. Computed relation between grain moisture content, drying time, and depth (Hukill, 28).

which a constant volume of air, of constant initial temperature and humidity, is continually blown in one direction.

In applying the chart to determine the moisture content at any point in a drying bin, after any period of dryer operation, it is necessary to express the moisture content, the depth of the grain to that point, and the time of operating the dryer in appropriate units. The required moisture content can then be read off the chart. The method of arriving at the proper units will be presented later, after a discussion of what takes place in a batch-drying process.

Specific Heat and Heat of Vaporization. Data in the literature on heat of vaporization of water in grains and on the specific heats of grains are very incomplete. Specific heats of wheat at a few moistures and temperatures are reported by Kelly (35). For purposes of approximation, Siebel's formula (62) may be applied to grain. No claims for its exactness have been made; it assumes that the specific heat of the water content of the grain is 1.0 and that of the dry material is 0.2. The formula is

$$S = 0.2 + 0.008\ M_w \tag{3}$$

where S is the specific heat of the material in Btu/lb.°F., and M_w is the moisture content, per cent wet basis.

The heat of vaporization for water in grain is higher than that for free water at the same temperature. The difference may be assumed to be equal to the heat of wetting, but experimental data on heat of wetting

are also scarce. The latent heat is greatest at low moisture content, and is very nearly the same as for free water at high moisture content. Winkler and Geddes (76) measured the heat of hydration of flour and starches. Their results are expressed in heat units per unit weight of dry material and cannot be translated directly to Btu per pound of water absorbed at each level of moisture content, because this would require analysis of the rate of change of heat of hydration. However, the data include the total heat of hydration when material of various initial moisture contents is wetted with excess water. The results indicate that the quantity of heat released when increments of water are added to flours and starches of very low moisture content (as low as 1.7%) is in the neighborhood of 200 calories per gram. They also show that, above 16%, added increments of water release much less heat. Two hundred calories per gram is 360 Btu per pound. If we assume, as appears logical, that the heat of hydration is the difference between the heat of vaporization of water in flour and that of free water, we can conclude that the heat required to dry flour must be the heat of vaporization of free water (in the neighborhood of 1,000 Btu per pound) plus 360 Btu. This is for removal of water at extremely low moisture contents. For drying in the region of 10 to 20% moisture content the heat of vaporization is considerably less. In the absence of accurate data a value of 1120 Btu per pound has been used (28).

Schrenk *et al.* (56) measured the heat of hydration of starch and found higher values than those of Winkler and Geddes, although the data are not strictly comparable. Results for various starches were from about 23 to 30 calories per gram of starch, as compared with about 20 calories as measured by the earlier workers. These experiments were all made with completely dry starch so that the heats of hydration for various moisture contents cannot be estimated from them.

The heat of vaporization might be computed from data on vapor pressure of the moisture in grain by the following close approximation of the Clausius-Clapeyron equation:

$$H_{fg} = V_{fg} T \frac{\delta P}{\delta T} \tag{4}$$

in which, H_{fg} is heat of vaporization, ft.-lb. per lb.; V_{fg} is volume of the vapor, cu. ft. per lb.; T is absolute temperature, °R.; and P is vapor pressure, lb. per sq. ft. Unfortunately, accurate measurements of vapor pressure of moisture in grain are also lacking.

General Comment. The preceding discussion provides a general picture of the current status of basic research on grain drying. All principal factors that affect drying rates appear to be known. But nothing like sufficient observational data are available to make possible the formula-

tion of precise mathematical laws for grain drying. There is a wide field here for further experimental work. The key problem obviously relates to the simplest case in which each kernel is fully exposed to air of constant temperature and humidity. Until this problem is solved—that is until an equation has been developed for these conditions that takes account of all the variables involved—bulk grain drying must remain an essentially empirical operation. The deficiencies in our knowledge will be apparent from the next section, which deals with some of the fundamental aspects of bulk drying and with the mathematics of the process as far as it seems possible to develop it from the information we have at the present time.

Theoretical Considerations

In this section the relations among various factors in bulk drying are discussed. The mathematical treatment of this section illustrates a way in which various drying processes may be interpreted to arrive at a general pattern of moisture changes in any grain bulk, although only the expressions for the simple batch process are derived. The heat balance which is expressed as a differential equation is valid in any adiabatic bulk drying process—whether batch, continuous counterflow, reversed air movement, or other—and is an essential part of any engineering analysis of bulk drying. An attempt has been made to keep this section independent of the others. This makes a certain amount of repetition unavoidable.

Significance of Wet Bulb Temperature. Consider a batch of moist grain of uniform initial moisture content in a bin with vertical sides. Drying air is forced into the grain through a perforated floor. The air moves upward at a constant rate, leaving through the upper surface of the grain. The temperature and humidity of the air entering the grain are assumed to be constant. As the air moves upward its humidity increases as a result of evaporation of moisture from the grain. The increase in air humidity is accompanied by a decrease in air temperature. The increase in humidity and the decrease in temperature of the air take place simultaneously and, since both are almost proportional to the quantity of heat used in vaporizing water, the total heat of the air remains practically unchanged. The wet bulb temperature is very nearly an expression of the total heat of the air, so the wet bulb temperature is almost constant as it passes through the grain. For practical purposes, it may be considered to be constant. The condition of the air as it passes through the grain therefore follows a wet bulb line on a psychrometric chart. The rate at which the air temperature drops depends upon how fast moisture is evaporated from the grain.

Heat Balance. The relationship that makes it possible to find the moisture content at any location at any time in bulk drying is the heat balance that must exist at every point in the bin at all times. The heat that is used in evaporating moisture from a kernel must equal the heat supplied to that kernel by the drop in air temperature, plus any heat supplied by a change in grain temperature, plus any heat supplied by conduction or radiation from the surrounding grain or bin walls. For practical purposes, the heat lost or gained through the bin walls is small and may usually be neglected; for simplicity, it will be neglected in our discussion. This leaves the heat balance between heat of vaporization, sensible heat of the air, and sensible heat of the grain. For further simplicity, the case when the sensible heat of the grain is negligible will be considered, although under some conditions this factor may have an appreciable effect on the drying rates. When it does, a correction can be applied to find how the initial grain temperature affects the computed moisture contents.

This reduces the heat balance to one in which the heat of vaporization of the moisture evaporated from the grain is equal to the sensible heat loss in the air passing the grain. This balance must prevail at every point in the bin at all times.

Consider a thin layer (δx) of grain at any height (x) in the bin. During a short time interval (δt) the moisture content (M) decreases slightly (δM). The quantity of heat required to decrease the moisture content by this amount is given by the product of the amount of water evaporated and the unit heat of vaporization. In symbols, this may be expressed as

$$L = W A \, \delta x \frac{\delta M}{100} \cdot V \qquad (5)$$

where W is the density of dry matter in grain, A is the cross-sectional area of air stream through grain, and V is the unit heat of vaporization of moisture in grain.*

During the same time interval the air moving through the thin layers undergoes a slight drop in temperature (δT). The heat loss associated with this drop in temperature is given by the product of the mass of air passing through the thin layer during the time interval, the specific heat of air, and the drop in temperature. In symbols, this may be expressed as

$$L' = 60 \, Q \, A \, \delta t \, S_A \, \delta T \qquad (6)$$

where Q is the mass rate of air flow, and S_A is the specific heat of air.

* A list of the symbols in this discussion, together with their definitions and dimensions, is given at the end of this section (pp. 420, 421).

Since the heat balance prevails throughout the bin, $L = L'$, and

$$W\,A\,\delta x\,\frac{\delta M}{100}\,V = 60\,Q\,A\,\delta t\,S_A\,\delta T \tag{7}$$

or

$$\frac{\delta M}{\delta t} = \frac{6{,}000\,Q\,S_A}{W\,V} \cdot \frac{\delta T}{\delta x} \tag{8}$$

This expression may be written as

$$\frac{\delta M}{\delta t} = P \cdot \frac{\delta T}{\delta x} \tag{9}$$

where $P = \dfrac{6{,}000\,Q\,S_A}{W\,V}$, a constant for any given set of drying conditions.

This differential equation (Eq. 9) may be phrased somewhat loosely in the following way: The rate of change of moisture content of any kernel is proportional to the difference between the temperatures of the air immediately above it and immediately below it. More precisely, the time rate of drying at a given point and a given time is proportional to the space rate of decrease in temperature of the air at that point and at that time. Now if an expression were available for the way in which the moisture content of fully exposed grain changes for various conditions of air temperature, air humidity, air velocity, and character and moisture of grain, this relation could be combined with the above heat balance equation to give the general expression for moisture content in bulk drying.

Fully Exposed Drying Rate. As stated earlier, the exact relation between the exposed rate of drying and the drying conditions has not been determined. An approximation is given by the equation for exposed drying,

$$M - M_E = \Delta M e^{-Kt} \tag{1}$$

In the absence of a more exact expression, this equation is used in combination with the heat balance equation to give the general moisture chart of Figure 4. To make use of the above equation for this purpose it is necessary to know how K is related to temperature, humidity, and air velocity. Experiments have shown that, in most conditions, the exposed drying rate is affected very little by air velocity. This does not refer to the effect of varying the volume of air in bulk drying but to the effect of varying the velocity past a fully exposed kernel. For the present purpose, the effect of varying air velocity on exposed drying rate is considered negligible. When sufficient experimental data have been compiled to show just what effect changing air velocity has on exposed

drying rate, this effect can be included in a more complete analysis.

Air Temperature Changes in Bulk Drying. The effect of changing temperature and humidity of the air upon exposed drying rate has already been discussed briefly. It was pointed out that in bulk drying these two variables change simultaneously in such a way that the wet bulb temperature is almost constant. Since the humidity is dependent on the dry bulb temperature in a given drying operation, it is necessary to consider only changes in the air temperature. At the very start of drying, as air moves upward through the grain in a drying bin, the time-rate of drying of the grain, and therefore the space-rate of drop in air temperature, decreases as the air ascends. The temperature drops at a slower and slower rate, approaching, towards the top of the bin, a temperature of equilibrium below which it will not fall. This limiting temperature (T_G) is that at which (having cooled at constant wet bulb) the relative humidity of the air is in equilibrium with the moisture content of the grain. On the psychrometric chart, T_G is located by first finding the point representing the initial condition of the air, i.e., the initial dry bulb temperature (T_0) and the wet bulb temperature (T_W). From this point the line of constant wet bulb is followed to the relative humidity of equilibrium with the initial grain moisture content. Read the dry bulb at this point to get T_G. For very wet grain, $T_G = T_W$, and for drier grain T_G is greater than T_W.

The rate at which T approaches T_G when all the grain is at a uniform moisture content depends upon the rates at which the moisture leaves the grain. As pointed out, the exact relation has not been determined, but for this discussion we will use the approximation

$$T - T_G = \Delta T e^{-Cx} \tag{10}$$

in which $\Delta T = T_0 - T_G$, C is the rate of cooling, and x is the distance from the bottom of the bin. This is equivalent to saying that when the grain is at a uniform moisture content, the air decreases in temperature, as it rises in the bin, at a rate proportional to the difference between the temperature at that point and the temperature T_G.

Separate Relationship Among Factors. In summarizing, we have arrived at the following approximations:

For grain fully exposed to constant drying conditions (such as the grain at the very bottom of the bin),

$$M - M_E = \Delta M e^{-Kt} \tag{1}$$

The rate of drying is independent of air velocity. For air moving through grain of uniform moisture content (such as a batch of grain at the beginning of the drying process),

$$T - T_G = \Delta T e^{-Cx} \tag{10}$$

Also, if the conduction and radiation losses and the sensible heat of the grain are neglected,

$$\frac{\delta M}{\delta t} = P \frac{\delta T}{\delta x} \tag{9}$$

With these conditions assumed, we can derive an expression for the moisture content at any time at any level in a bin in which air of a constant initial condition is blown at a constant rate through grain having a uniform initial moisture content. Such an expression would give M as a function of t and x. A similar expression for the air temperature at each point in the bin could be derived giving T as a function of t and x.

We know that: when $t = 0$, $M = M_o$, and $T = \Delta T e^{-Cx} + T_G$;
when $t = \infty$, $M = M_E$;
when $x = 0$, $T = T_o$, and $M = \Delta M e^{-Kt} + M_E$;
when $x = \infty$, $T = T_G$;

and that, for any values of t and x, $\delta M/\delta t = P\ \delta T/\delta x$

General Relationship Among Factors. The functions

$$M - M_E = \frac{\Delta M e^{Cx}}{e^{Cx} + e^{Kt} - 1} \tag{11}$$

and

$$T - T_G = \frac{\Delta T e^{Kt}}{e^{Cx} + e^{Kt} - 1}. \tag{12}$$

in which

$$C = \frac{K \Delta M}{P \Delta T}, \tag{13}$$

satisfy all the above conditions, so that

$$M = \Delta M \frac{e^{Cx}}{e^{Cx} + e^{Kt} - 1} + M_E, \tag{14}$$

and

$$T = \Delta T \frac{e^{Kt}}{e^{Cx} + e^{Kt} - 1} + T_G. \tag{15}$$

These expressions for M and T make it possible to predict approximately the moisture of the grain and the temperature of the drying air at any level in the bin at any time, for a given set of drying conditions.

Since the Equations 1, 9, and 10, and the assumption regarding effect of air velocity, are only approximately true, the bulk drying equations derived from them are also only approximate. Tests of drying in bulk (28) show that the approximation is accurate enough to be useful, but results in underestimation of the time required for drying to low moisture levels. When more exact relationships are developed for exposed drying rate, a similar process to the above will yield a more exact expression for bulk drying rate.

Simplified Form of General Equation. The equation for M is useful in predicting the effect of variation in each of the factors affecting drying rate, but because of the large number of constants and in order to plot the equation as in Figure 4, it is simpler to use a form in which the units of moisture content, temperature, time, and depth are defined in such a way as to simplify the constants. First, the moisture content can be expressed in terms of a ratio, that is, the moisture ratio,

$$m = \frac{M - M_E}{\Delta M} \tag{16}$$

Before drying, $m = 1.0$, and at equilibrium, $m = 0$. The time can be expressed in terms of periods of half response; that is, one period (H hours) is the time required for fully exposed grain to reach a moisture ratio of 0.5 under any given set of conditions. Accordingly, $e^{-KH} = 0.5$ or $e^{KH} = 2$; and the time, in periods of half response, is

$$Y = t/H \tag{17}$$

The unit of equivalent depth (D) can be defined as the depth which contains enough grain to make the heat requirement for evaporating its moisture, from an initial moisture ratio $m = 1.0$ to a final moisture ratio $m = 0$, equal to the sensible heat supplied by all the air in one unit of time if its temperature is dropped from T_0 to T_G. At any level in the bin, the equivalent depth is D if

$$D = \frac{x\ WV\ \Delta\ M}{6{,}000\ Q\ S_A\ H\ \Delta\ T} \tag{18}$$

If these units are used, Figure 4 is a graphical representation of the equation

$$m = \frac{2^D}{2^D + 2^Y - 1} \tag{19}$$

This is the simplified form of the general drying equation. By translating a given set of drying conditions to these units and using the equation or Figure 4, it is possible to estimate when the top layer (or any other layer) will reach a desired moisture content. By thus estimating the drying time and final moisture content for various sets of drying conditions, the effect of changing rates of air flow or other factors on economy or uniformity of final moisture content can be estimated.

Application of General Equation. The use of Figure 4 is illustrated in the following example:

Grain sorghum 10.8 inches deep is to be dried in a bin by blowing 20 c.f.m. per sq. ft. of air upward through it from a space under a perforated floor. The conditions are as follows:

Density of dry matter in grain, $W = 35.2$ lb./ft.³
Initial moisture content, $M_o = 21.9\%$, dry basis.
Depth of grain in bin (10.8 in.) $x = 0.9$ ft.
Initial condition of drying air: dry bulb $T_o = 86.5°F.$;
wet bulb $T_w = 69.6°F.$; and
relative humidity $= 42\%$.

Quantity of drying air (20 c.f.m.) $Q = 20/14.0 = 1.43$ lb./ft.² min. From moisture humidity equilibrium curves, $M_E = 12.1\%$, dry basis. From tests of exposed drying rate for sorghum at 86.5°, $H = 1.8$ hr. Assume $V = 1170$ Btu/lb. and $S_A = 0.24$ Btu/lb.°F. From psychrometric chart,

$$T_G = 73.0°F.$$
$$\Delta M = 21.9 - 12.1 = 9.8\%.$$
$$\Delta T = 86.5 - 73.0 = 13.5\% °F.$$

From these values, and considering a column of grain 1 sq. ft. in cross section, the equivalent depth D of 10.8 in. of grain is

$$D = \frac{0.9 \times 35.2 \times 1170 \times 9.8}{6{,}000 \times 1.43 \times 0.24 \times 1.8 \times 13.5} = 7.25 \text{ (from Eq. 18).}$$

The top layer of grain in the bin will dry along the line $D = 7.25$. If we wish to know when the top layer will reach 17% dry basis, for example, we compute the moisture ratio for 17%:

$$m = \frac{17.0 - 12.1}{9.8} = 0.50 \qquad \text{(from Eq. 16).}$$

We then read from the chart, Figure 4, the time at which line $D = 7.25$ crosses $m = 0.50$. This occurs at $Y = 7.4$. Since $Y = t/H$, the time in hours is $YH = 13.3$; that is, the top layer will reach 17% in 13.3 hours. The moisture in any other layer or at any other time can be estimated similarly.

Nonadiabatic Drying. The effect of initial temperature of the grain is neglected in the equation represented in Figure 4. When the grain is much warmer or colder before drying than its final temperature, the heat given up or absorbed in changing its temperature may be a substantial part of the heat balance. This is particularly true when the change in moisture content is small. In this case the computation can be made more accurate by treating the sensible heat as part of V in the formula for D. To make this correction use V_1 in the equation instead of V. The sum of the sensible heat and heat of vaporization is thus:

$$V_1 = V + (T_o - T_1)\left(1 + \frac{20}{\Delta M}\right) \tag{20}$$

in which T_1 is the initial temperature of the grain, °F.

Thermal Efficiency. When artificial heat is used in drying grain, ther-

mal efficiency is important. In most grain-drying processes the heat for vaporizing moisture is supplied by air which is heated and passed through the grain. Generally, only part of the heat supplied to the air is available for drying. The heat supplied to the air is the quantity of air times the specific heat times the temperature rise. The heat used for drying is that given up by the air while passing through the grain; it is the quantity of air times its specific heat times the temperature drop. The thermal efficiency, neglecting radiation losses, may be defined as the ratio, expressed as a per cent, of the temperature drop of the air on its way through the grain to the temperature rise of the air as it is heated before passing through the grain.

$$E = 100\frac{T_o - T_F}{T_o - T_a}$$

in which E $=$ thermal efficiency, per cent,
T_o $=$ temperature of heated air, °F.,
T_F $=$ temperature of air leaving grain, °F., and
T_a $=$ atmospheric temperature, °F.

As pointed out earlier, the air may leave the grain at temperature T_G or higher. Evaporation cannot reduce the air temperature below T_G, so that the maximum theoretical thermal efficiency is

$$100\frac{T_o - T_G}{T_o - T_a}$$

If the air does not stay in contact with the grain long enough to pick up its maximum load of moisture, then the efficiency is less than the theoretical maximum. In a batch-drying process, such as that discussed earlier, if drying is continued until the upper layer is partly dry, T_F will be higher than T_G, and the maximum drying efficiency will not be attained.

Examination of Figure 4 will illustrate this. Line zero shows how the moisture in the bottom layer of grain changes. Line one shows the changing moisture content of the grain at a depth of one unit. If there are "D" pounds of grain (depth factor of one) in the dryer, then line one shows the moisture at the top of the grain, that is, where the air exhausts from the grain. If there is more grain, the upper layers will change as shown by the successive lines. When the drying air reaches the grain corresponding to line one it still has capacity for removing moisture at that point but less rapidly than when it entered the bin. As the air passes successive layers, its capacity for removing moisture becomes less and less. For example, by the time it has reached line 5 it has become almost saturated and does very little drying until the dryer has been in

operation for some time. After a period of two or three time units the moisture content at line 5 drops more rapidly because, by that time, the grain below has dried considerably and the air at that point has not become so nearly saturated by moisture from the grain below.

If there are only "D" pounds of grain (depth factor of one) it will be seen that the air is exhausted from the grain without having become nearly saturated; it still has considerable drying capacity, and the efficiency is low because the air is exhausted from the bin without picking up its maximum load of moisture. If there is more grain, more of the drying capacity of the air is used and the efficiency is higher. In general, the more grain in the bin the higher the efficiency, but beyond a depth factor of 4 or 5 the efficiency may not increase very fast.

Uniformity of Drying. At the end of any period of drying there is not much difference in moisture content between the top and bottom layers of the bin when the grain is only one unit deep. At five units, on the other hand, the top has dried little when the bottom is almost completely dry. At greater depths, "zone drying" is very noticeable; that is, drying occurs first in the lower layers only. When they have dried, the grain next above starts to lose moisture, and the zone in which drying takes place moves gradually upward until the whole bin is dry. This occurs only when the equivalent depth, as computed for use in the chart, is relatively large. A depth unit may be only a fraction of an inch or it might be several feet, depending upon the factors involved.

General Comment. This section has shown how a mathematical formula can be derived for predicting the approximate moisture content of the grain at any level in a batch dryer under a given set of conditions. Before an exact formula can be developed and used for accurate predictions of performance of practical grain dryers, it is clear that much additional information for the various grains will be required regarding the following factors: (1) heat of vaporization of moisture at different grain moisture levels; (2) moisture-humidity equilibria; and (3) exposed drying rates at different grain moisture levels using air at different temperatures, humidities, and velocities.

Definitions and Dimensions of Symbols Used in This Section

M = moisture content of the grain, percentage dry basis, lb./lb. $\times$ 100.
t = time from start of drying, hours.
x = distance from bottom of bin, feet.
T = dry bulb temperature of air, °F.
L = heat involved in heat balance, Btu.
V = unit heat of vaporization of moisture in grain, Btu/lb.
A = cross-sectional area of air stream through grain, ft.^{2}
W = density of dry matter in grain, lb./ft.^{3}
Q = mass rate of air flow, lb./min.ft.^{2} ($60Q$ = lb./hr.ft.^{2}).
S_A = specific heat of air, Btu/lb.°F.

M_E = equilibrium moisture content, per cent, dry basis (see p. 404).
M_o = initial moisture in grain before drying, per cent, dry basis (see p. 403).
$\Delta M = M_o - M_E$, per cent dry basis (see p. 403).
K = drying constant in equation (1) (see p. 407).
C = rate of cooling of air passing through grain of uniform moisture content (see p. 415).
T_o = initial temperature of drying air, °F.
T_u = air temperature of moisture equilibrium at constant wet bulb, °F. (see p. 415).
$\Delta T = T_o - T_u$, °F.
m = moisture ratio $M - M_E/\Delta M$ (see p. 417).
H = period of half response, hours (see p. 417).
Y = time in dimensionless units = t/H (see p. 417).
D = equivalent depth = $x\, W\, V\, \Delta M/6{,}000\, Q\, S_A\, H\, \Delta T$ (see p. 417).

Practical Considerations

There are a number of different methods in use for practical grain drying, some of which will be illustrated. The principal considerations in choosing a dryer are drying capacity, cost of installation, safety of operation, control of drying temperature, uniformity of output, and suitability of handling equipment. Ease of cleaning is also important, particularly if the dryer is to be used for seed grain. Types of damage that may occur to grain as a result of drying include: loss of germination; scorching; hardening of kernels, which makes milling difficult; reduction in baking quality; checking, especially in rice, which results in broken kernels; and possible reduction in palatability or nutritive value in feed grains. Molding during drying may occur if the drying process takes too long.

Batch and Stage Drying

In batch drying the thermal efficiency may be high, but only if the grain is several units deep. On the other hand, the final moisture content will be relatively uniform only if the depth of grain is small or if drying is continued until all the grain is near the equilibrium moisture content. Usually it is not economical nor desirable to dry grain to extremely low moisture content. In batch drying, then, one has to choose between fuel economy and uniformity of final grain moisture.

Stage drying is a modified batch process in which more uniform final moisture can be achieved without sacrifice in economy. The air is passed in series through two or more bins. While the grain in the first bin is being dried to the desired moisture content, the grain in the second bin is partially dried by exhaust air from the first. At the conclusion of this stage, air direct from the heater completes the drying in the second bin and the exhaust air passes to a third. Meanwhile, the first bin is emptied and refilled. Extreme overdrying is thus avoided though the drying air is used almost to capacity. If each batch in this process contains about two or three depth units, the uniformity and economy may be relatively

good. Many processors of hybrid seed corn use two or three stages in drying ear corn for seed.

Sweating During Batch Drying. When heated air is used for batch drying, the top layers of grain frequently become wetter during the early part of the drying period (67). This is sometimes called "sweating." It occurs if the grain is initially colder than the exhaust air temperature or if there is loss of heat by radiation from the upper surface. If the grain depth is over four or five units, sweating is likely to occur. The effect of this temporary wetting on fuel economy is not serious because the moisture condensed on the grain releases its heat of vaporization to the grain. Sweating may be serious, however, because molds may develop on the grain if the grain moisture and temperature are maintained at high levels for long periods. With ear corn, if drying is completed in less than about a week, little damage will usually result. When heated air is used it is important to have sufficient capacity in the equipment to dry all layers completely before any damage due to high humidity and temperature can occur.

Continuous Drying

Continuous flow dryers are used for shelled corn and small grains. The grain may be made to flow by gravity while the rate of discharge is controlled by mechanical means. Air is passed through the grain as it moves downward, and this may be done in different ways. With respect to the drying rates in successive layers of grain, continuous flow dryers are not necessarily different from batch dryers. For example, if the air moves horizontally through an unagitated downward moving column of grain, the drying proceeds as in a batch dryer, and the limitations as to economy and uniformity are about the same as for batch drying. If the air is passed successively through a lower section of the column, then through an upper section, the process is about the same as in a two-stage batch dryer. If the grain is thoroughly agitated in a single-pass continuous dryer, the uniformity of final moisture content may be good but the thermal efficiency cannot be high. In order to have high thermal efficiency the leaving air must have been in contact with wet grain long enough for its temperature to have dropped almost to the level (T_G) at which the relative humidity of the air is in equilibrium with the moisture content of the grain.

Three types of commercial dryers are illustrated in Figures 5, 6, and 7. These are usually installed at processing plants or grain elevators and, as a rule, utilize either gas or fuel oil. In most dryers the products of combustion are mixed with the drying air to avoid the necessity for expensive heat exchangers and the accompanying stack losses of heat. With complete combustion, the stack gases do not adversely affect the grain. A

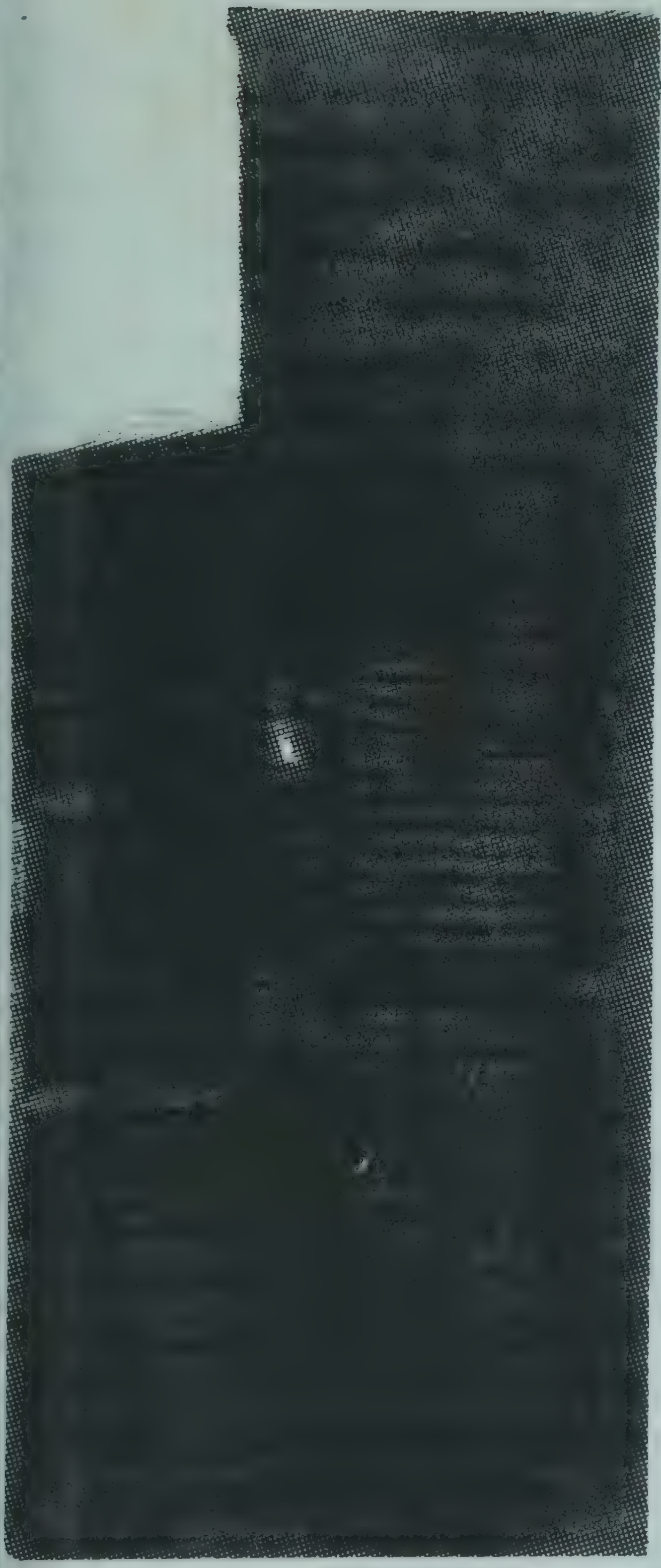

Fig. 5. View of drying and cooling sections of a Randolph Grain Dryer. (Courtesy O. W. Randolph Co.)

certain amount of water is formed during combustion; with fuel oil, for example, about a gallon of water from each gallon of oil. But this addition of moisture to the drying air has a relatively small effect.

The dryer in Figure 5 has an upper and a lower compartment. Heated air is passed through the grain in the upper section where most of the drying is done, and air at atmospheric temperature is forced through the lower one for cooling. Some additional drying is accomplished in the cooling section but its main purpose is to avoid putting the dried grain in storage while it is hot.

Figure 6 shows a dryer in which the heated air is introduced at many points in the grain bulk through the channels which are shaped like inverted V's. Alternate sets of channels serve as discharges for the air. The air moves vertically from an intake channel to a near-by exhaust channel, meanwhile passing through and drying the grain.

Figure 7 shows a dryer in which the grain moves from one end of the drying compartment to the other in a thin layer on a continuous belt. The belt is of open network so that the air may pass through it and into the grain.

Commercial dryers used for wheat, shelled corn, and oats are usually designed to operate with air heated to about 200°F. High temperatures result in high capacity in pounds of water removed per hour. The maximum theoretical thermal efficiency is also usually higher at high temperatures.

Grain dryers have been used at terminal elevators for years in both the United States and Canada. Recently a large number of local elevators, particularly in the corn belt, have installed drying equipment. Artificial drying of wheat, oats, corn, and similar grains has been looked

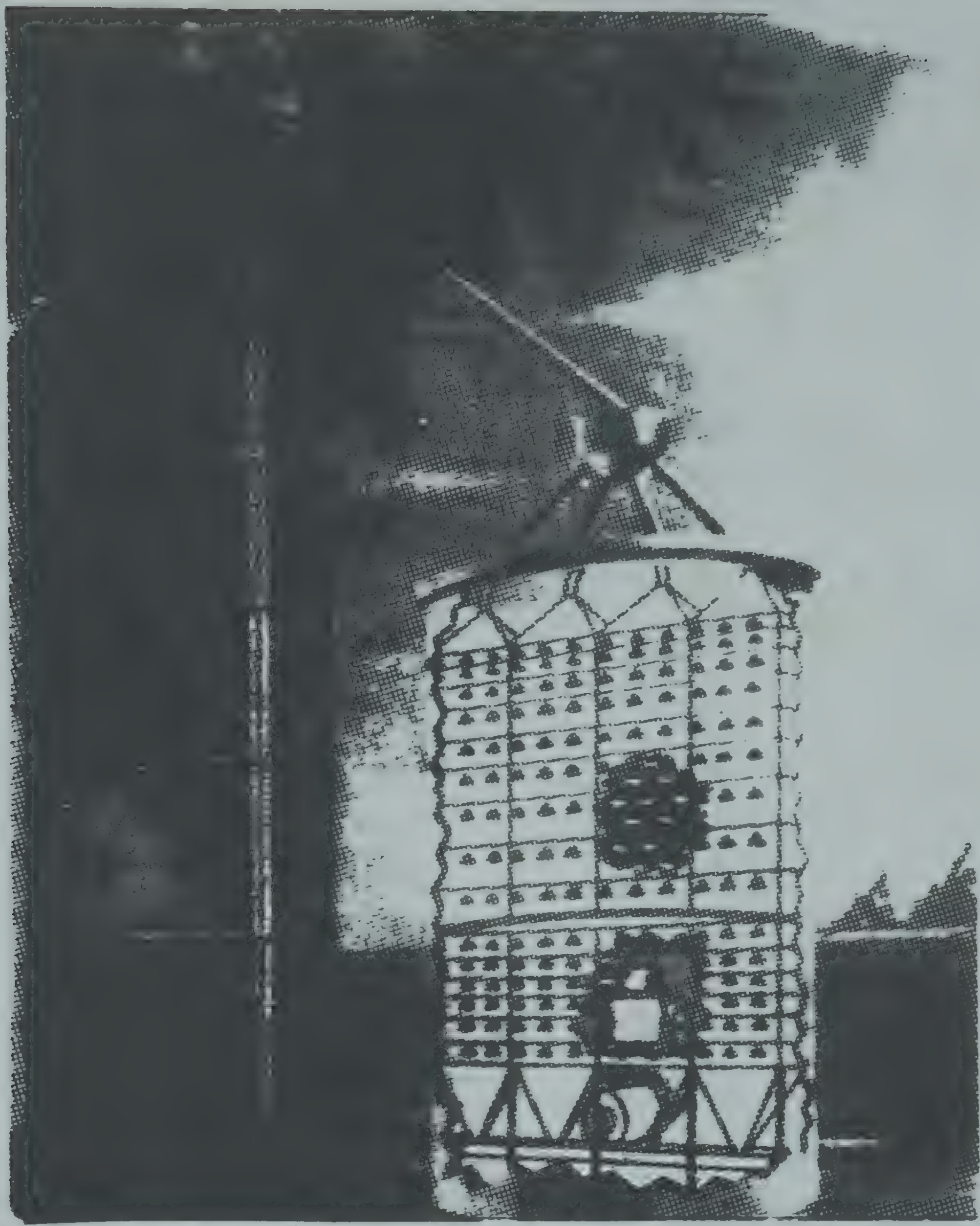

Fig. 6. Cutaway view of Campbell Dryer. (Courtesy Campbell Heating Co.)

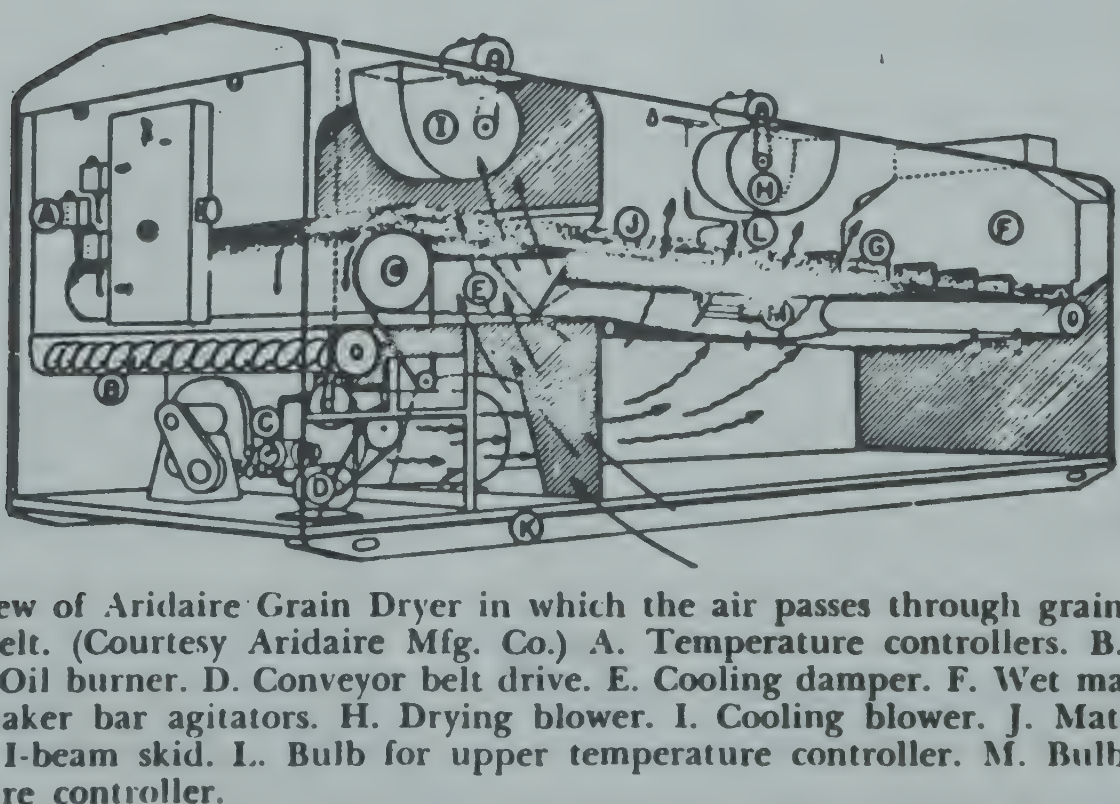

Fig. 7. View of Aridaire Grain Dryer in which the air passes through grain on a continuous belt. (Courtesy Aridaire Mfg. Co.) A. Temperature controllers. B. Discharge auger. C. Oil burner. D. Conveyor belt drive. E. Cooling damper. F. Wet material hopper. G. Raker bar agitators. H. Drying blower. I. Cooling blower. J. Material being dried. K. I-beam skid. L. Bulb for upper temperature controller. M. Bulb for lower temperature controller.

upon as an emergency measure to prevent deterioration in occasional damp lots of grain. Changes in farming methods, however, including more complete mechanization, are resulting in more dependence on artificial drying as part of the farm routine in handling grain.

Effects of Drying

On Milling Quality. Wheat millers have observed that if grain is dried at too high a temperature it becomes "case hardened" and more difficult to mill. Wet millers of corn find difficulty in the separation of starch from corn that has been dried at high temperatures. The exact temperatures causing this difficulty are not known, and the wet millers avoid using any artificial dried corn if possible. Wagner (73) says of artificially dried corn for wet milling, "We do not know what temperature we could tolerate, but typical 180°F. drying is clearly too high for our purposes."

Mounfield (44) reported improvement in milling character of wheat after artificial drying and a slight improvement in baking quality when Manitoba wheat was dried at air temperatures of from 160° to 240°F. The safe drying treatment is said to be a hot-air temperature of 180°F. and 1.82 cu. ft. per minute per pound of grain, with a maximum grain temperature of 130°F. attained over a period of about an hour. These limits can be exceeded if the initial moisture is less than 20% (wet basis).*

An extensive set of drying tests is described in detail by the National Research Council of Canada (46, 67). The papers include tables of drying test data and describe methods of testing dryers and testing the wheat after drying. Pilot-plant tests showed no damage to baking quality in most cases and only slight damage in a few. An appendix by Geddes to the same paper points out that heat treating of wheat results in poorer baking quality of the flour in certain baking processes, while the same treatment may improve baking quality when other baking methods are used. The maximum safe air temperature for drying wheat is concluded to be 180°F.

Since 1929, when these studies were published, drying operations in Canadian terminals have been supervised by the Board of Grain Commissioners, whose regulations permit a maximum air temperature for wheat drying of 180°F. Later Canadian studies† have shown that space variations of as much as 30°F. may occur in certain dryers. Each dryer is equipped with a recording thermometer, but the temperature recorded depends on the location of the thermometer bulb and on whether it is shielded from radiated heat. Drying operations are checked by means

* Throughout the remainder of this chapter, all moisture contents are given on a wet basis.
† Private communication from J. A. Anderson, Chief Chemist, Board of Grain Commissioners for Canada, Winnipeg, Manitoba.

of milling and baking tests whenever drying is started in any terminal. It has been found that few dryers can operate with temperatures of over 175°F. without changing the baking quality of the wheat.

On Germination. Grain that is to be used for seed, or barley for malting, cannot be dried at excessive temperatures without destroying the germinating power (6, 7, 37, 38, 75). In drying seed corn and malting barley it is customary to limit drying air temperatures to a maximum of about 110°F. (15). For other grains, limits in temperatures may be somewhat higher.

With corn, for example, Dimmock (14) showed that a drying temperature of 108°F. does not injure germination of corn with an initial moisture up to 35% (wet basis), but wetter corn is injured. He also found a variation among hybrids in this respect. Wileman and Ullstrup (75) found that temperatures up to 120°F. can be used with corn of 25% moisture or less, but above 25% the drying temperature should not exceed 110°F. Koehler and Dungan (38) found that corn artificially dried in 4 days to one month germinated and yielded better than similar corn dried naturally over a period of 4 months. Aicher (1) dried buffalo grass seed and reports that proper treatment and drying increase germination six to eight times. Other observations on effects of artificial drying are given by Burgess (7), Harrison and Wright (20), and by Duncan and Marston (16). Boswell *et al.* (6) report germination tests on vegetable seeds dried at 150° and 120°F. and subsequently stored at various temperatures and humidities; 3 hours' drying at 150°F. reduced germination.

Hutchinson (30, 31) found that very dry wheat could withstand high temperatures without loss of germination. He proposed two equations which represent the upper and lower boundaries of the zone of damage to germination. They are: for the upper limit, $\theta = 130.3 - 5.4 \operatorname{Log}_{10} t - 43.87 \operatorname{Log}_{10} m$; for the lower limit, $\theta = 122.0 - 5.4 \operatorname{Log}_{10} t - 43.87 \operatorname{Log}_{10} m$; where, $\theta =$ temperature °C., $t =$ time of exposure to temperature in minutes, and $m =$ moisture content of wheat, per cent. These equations are said to apply within the range of 35 to 14% moisture content.

On Nutritive Value. Yung (77) dried corn at temperatures from 190° to 200°F. No damage was visible in the ear corn, but shelling showed the germ ends of the kernels to be shriveled, somewhat brittle, and discolored. Rapid drying at 300°F. caused visible discoloration in ear corn. The corn was not significantly different from that dried at room temperature with regard to carotene and amide nitrogen content. Feeding experiments with white rats gave inconclusive results as to the effect of temperature on nutritive value.

Note on Rice Drying. Rice drying (9, 17, 41, 64) presents a special problem because production and harvesting methods require that prac-

tically all the rice crop be dried artificially. Engler and McNeal (17) state that it is desirable to harvest rice with a moisture content between 20 and 26%. Rice is dried with the hull on and is later hulled and milled. High temperatures and fast removal of moisture result in checking or cracking of the kernels, so that it has been found necessary to limit the temperature of the drying air and to limit the amount of moisture removal in any one pass through the dryer. Stack burn in rice and the problem of dust control are discussed by Kramer (39) who reports that stack burn does not occur in the dryer and may be prevented by limiting the time between passes. The drying air temperature is usually held below 120° to 130°F. and not more than 2 or 3% of moisture is removed at one time. After going through the dryer the rice is held in a tempering bin for half a day or so before being put through the dryer again; this process is repeated enough times to get the desired final moisture content. McNeal (41) describes rice drying experiments. The yield of head rice was increased by using up to three dryings at 130°, for example.

Farm Drying

Until recently farm grain drying has not been practiced very extensively. With electric power more widely available and machinery of more and more kinds being used on farms, farm grain dryers are coming into use more generally. Air heating equipment for use on farms is now made by a number of manufacturers. These units generally consist of a blower and a heater with necessary power unit, combustion controls, and accessory equipment. Most of them are designed to burn fuel oil and are equipped with domestic oil burners of the pressure atomizing type. Power is usually supplied by an electric motor, but some dryers are equipped with a gasoline engine. The dryers are of two general types, "direct heat" units passing the products of combustion into the drying air, and "indirect heat" units using heat exchangers and discharging the products of combustion through a stack to the atmosphere.

Perhaps the greatest deterrent to more extensive use of heated air farm dryers is the fire hazard. A number of costly fires have occurred as a result of using such dryers during the development stage. No doubt improved control and safety devices will eventually reduce the fire hazard to that comparable with other commonly used combustion equipment such as domestic furnaces.

Ear Corn Drying. Corn, ripening as it does in the early fall, usually contains too much moisture at harvest time to be shelled and stored immediately. If it has dried to about 20% moisture in the kernels while on the stalk, the husked ears can be put in a ventilated crib (58) where the wind further dries it, and by late spring the ears may be dry enough

to shell and produce shelled corn that may be stored safely. If the growing season is unfavorable or if the weather at harvest time is unusually poor for natural drying, special handling is necessary or the corn may spoil. Changes in farming methods are making natural drying more uncertain. Since a large part of the corn crop is consumed on the farm, and because of transportation costs, particularly for corn on the cob, central drying plants cannot be expected to meet the entire need for mechanical drying.

The relations between amount of corn, volume of air, and rate of heat supply for practical farm drying were outlined in a special committee report (65). It was recommended that, for ear corn having a kernel moisture content of 30%, Table II be used as a basis of dryer design.

TABLE II

FAN CAPACITY AND APPROXIMATE DRYING TIME FOR VARIOUS FUEL RATES WHEN DRYING 1,000 BUSHELS OF EAR CORN FROM AN INITIAL MOISTURE CONTENT OF 30%, WET BASIS (65)

Heater Capacity	Fan Capacity	Approximate Drying Time
gal. per hr.	*cfm*	*days*
4.0	5,400	4 to 6
2.0	3,600	8 to 12
1.0	2,700	16 to 24
0.5	2,700	32 to 48

Figures 8 and 9 show farm type units. The greatest use made of this type of equipment has been for drying ear corn, although shelled corn and small grains can be dried also. These units, particularly those having heat exchangers, have also been used for mow hay drying. The U.S. Department of Agriculture in cooperation with several state experiment stations recently made a study (11, 23, 25, 29, 59, 69, 70, 71, 72) of farm dryers for corn. The study included tests and observations on drying ear corn on farms in some 86 cribs. In all cases the drying was successful in the sense that the corn was dried to the desired moisture content and damage to the grain due to the drying was negligible. The study left no question that farm grain drying with heated air can be successful and dependable, its practicability depending entirely upon economics.

When ear corn is dried artificially on the farm, it frequently is done in an ordinary storage crib. Heating units provide heated air for drying,

Fig. 8. Drying air heater, in which products of combustion are mixed with the drying air, connected to a corn crib for drying ear corn.

Fig. 9. Using a temporary round crib for drying ear corn with a portable indirect air heater in which a heat exchanger is used to heat the drying air.

but in order to apply it to the corn, special preparation of the crib is necessary (59). The air must be introduced in such a way that it moves more or less uniformly through all the corn; otherwise excessive fuel and power are required. This is accomplished by using paper or canvas to cover some of the walls to make them airtight. Perhaps the best

arrangement for batch drying (59) is to have the corn on a perforated floor which is set sufficiently above the permanent floor so that all the corn is exposed to about the same volume of air flow. The walls in this case must be airtight and there must be an opening above the level of the corn to permit the air to escape.

This arrangement is difficult to apply in some cribs and the commonest way of drying cribbed corn (59) is to make both ends of the crib airtight and cover the upper part of one side wall with canvas or paper, leaving the bottom 3 or 4 ft. of that wall uncovered. A duct, usually of canvas, is applied along the full length of the lower part of the wall in such a way that air can move from the duct through the open boards of the crib. Some of it then moves horizontally through the corn to the other side, some to the upper surface of the corn, fanning out to give a reasonably uniform distribution. Figure 8 shows a drying unit connected with a crib in this manner. Many variations in the method of applying warm air to ear corn are used. Figure 9 shows corn being dried in a round temporary crib. With such arrangements corn can be dried to a safe moisture content in 3 or 4 days if the equipment has suitable heating capacity and air volume. If the heating capacity is not sufficient, the drying in the upper and outer layers will be slow, and prolonged exposure to the warm saturated air will cause spoilage at these locations.

For drying ear corn with heated air, temperatures of less than 60° to 70° result in slow drying. Most units are designed to operate at 60° to 80° above atmospheric temperature, although some use 200°F. or higher.

To reduce the moisture content to a safe level, it may be necessary to evaporate 2 gal. or more of water from each bushel of ear corn. In drying, the corn shrinks and the top may settle as much as 3 ft. in a crib 14 ft. deep at the start. Much of the water in ear corn is in the cob, especially immediately after harvest. When corn is dried on the cob considerably more heat is required than when it is shelled before drying. Schmidt (55) discusses the relation between moisture in kernel and that in cob.

Drying Small Grains on the Farm. Shelled corn and small grains may be dried on the farm with the same equipment used for ear corn. The grain may be put in a bin having a false floor so that air can be forced upward through it. Several designs have been suggested for special drying compartments through which the grain flows in a continuous process. For example, plans for such a dryer were published by the Texas Experiment Station (40).

One of the limiting factors in drying small grains is the resistance

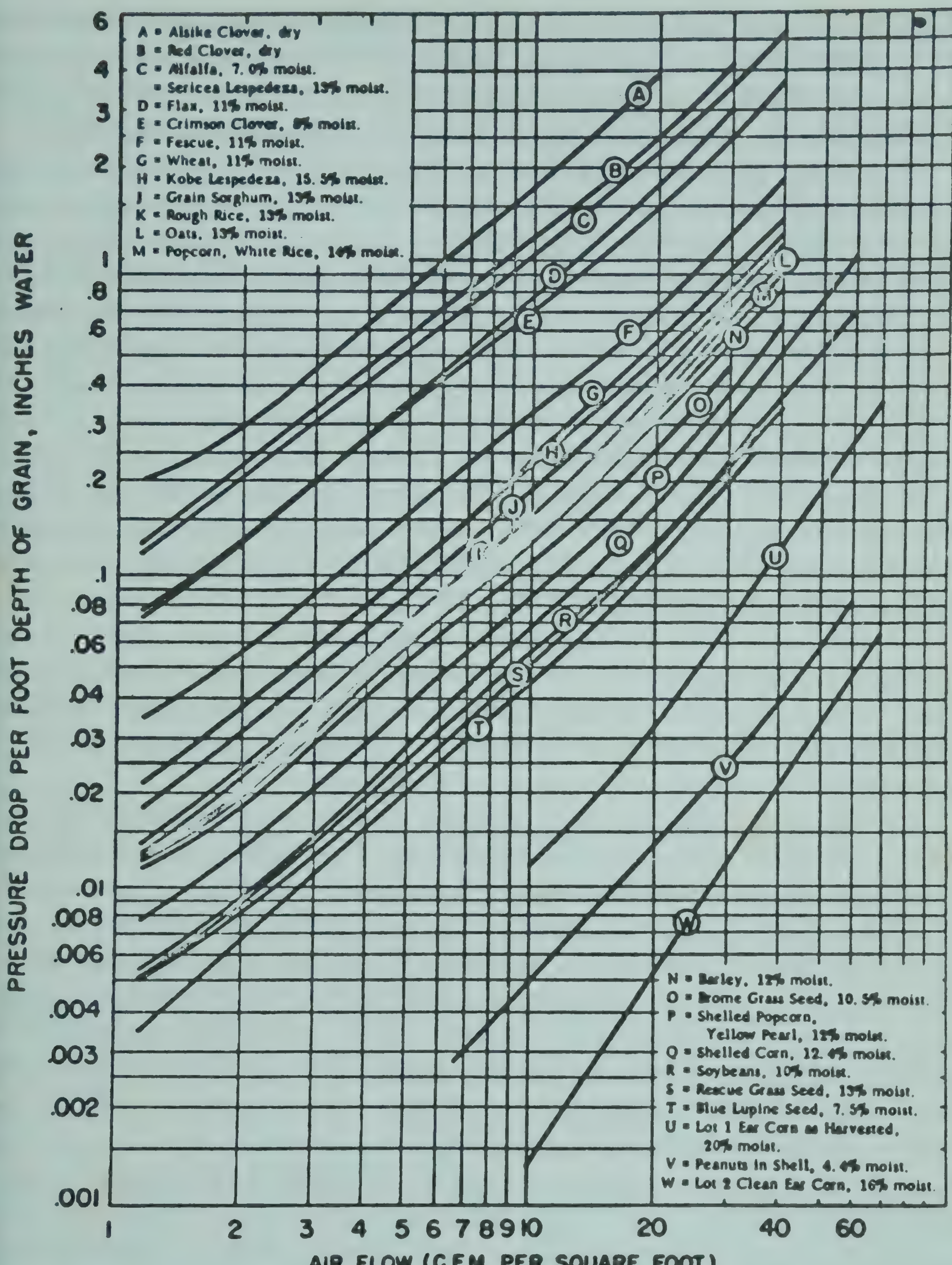

Fig. 10. Relation between rate of air flow and pressure drop per foot for various grains. The pressure drop is modified by compaction and moisture content. Data on these factors are given in reference 59a.

to air flow and the power required to force air through deep layers. When shelled corn is dried in a depth of as much as 10 ft., excessive power is required to force sufficient air through the grain. The power

required to force a given volume of air per bushel increases as about the third power of the depth. Figure 10 shows the relation between air volume, grain depth, and air pressure for some grains (21, 22, 57, 59a, 68). Similar data for some other grains have been compiled by Stahl (66).

Burkhardt (8) designed a dryer in which air moves upward through a downward moving column of grain. The air is not heated prior to entering the grain, but heat is supplied by steam or hot water coils with extended surfaces which are located in the drying compartment. Kelly (34, 36) describes a dryer in which unheated air is blown through grain. The heat for drying in this case is supplied by preheating the grain. A farm rice dryer in which heated air is blown through inclined layers of rice is described by Barger *et al.* (2). The rice flows from one inclined tray to the next, and air flows upward through perforations in the trays: with two or three trays, one above the other, the rice is dried in stages. Price and Branton (53) describe ear and shelled corn dryers and recommend recirculation of a portion of the exhaust air to reduce the variation of moisture content in shelled corn.

Nicholas and Musser (49) describe experiments in which the heat for drying grain is supplied by infrared electric lamps. The possibility of using a heat pump for utilizing electric energy has also been suggested (50), but no specific practical arrangement for its use has been found in the literature.

Drying with Unheated Air. Artificial drying with unheated air has been used, particularly on Ohio farms (61). This requires a much longer time and depends upon favorable atmospheric conditions for success. One advantage of using unheated air is the freedom from the fire hazard that goes with combustion equipment. The first cost of atmospheric dryers is less too. In dry climates, wind ventilation alone can accomplish some drying if the grain is in specially constructed bins provided with special ventilation cowls and having perforated walls (33). Fenton (18) states that natural ventilation should take care of grain having 15 to 16% moisture placed in storage during the cool weather of late fall in the climate of western Kansas. At present, unheated air is being used successfully for drying grain with higher moisture content. Ear corn and shelled corn with initial moisture as high as 25 to 30% are dried, using air volumes from 3 to 7 cu. ft. per minute per bushel of grain. The practice of drying grain on farms with unheated air is increasing rapidly.

Chemical Desiccants. Chemical absorbents have been used for drying grain at least experimentally. Oxley (50) suggests drying by mixing granular desiccants intimately with damp grain. He mentions a British patent (42) in which silica gel is mixed with damp grain. Simons (63) describes a dryer which utilizes calcium chloride for absorbing the

moisture in drying grain, particularly blue lupine seed. Dexter and Creighton (13) describe absorbent blocks which are impregnated with drying salts for imbedding in stored grain to reduce its moisture.

General Comment. All methods of drying grain after it is harvested, from spreading in thin layers in the sunshine or wind to the use of heat and forced ventilation in special drying compartments, depend on having each kernel exposed to a drying environment for long enough to lose the desired amount of moisture. The time necessary to get a substantial loss in moisture presents a very real problem in farm drying. The method of drying used, or whether mechanical drying is used at all, may depend on how many man-hours can be spared for the job, what kind of mechanical conveying equipment can be made available, and how the drying process can be fitted in with the other farm operations. By one method or another, however, mechanical grain drying on the farm is becoming more and more common, and undoubtedly, for some grains at least, it will eventually be depended upon as a routine for removing some of the hazards of weather and climate.

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Flour Storage in Bulk

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The concentration of milling capacity in large modern units and the accompanying changes in merchandising methods have made the storage of wheat and mill products problems of major importance.

Wheat presented the most acute problem because it is produced in a short season and must be stored in convenient locations to keep the mills operating throughout the year. The development of large concrete grain silos provided a satisfactory solution to this problem.

Flour and other mill products, until recently, were stored almost entirely in sacks or barrels in multifloor warehouses; the only accumulation in bulk was the small amount held in the packer bins, and this was never more than the mill's production for a few hours.

Today the trend is toward the installation of large capacity bins that may hold many hours' production of the mill. From such bins the flour is drawn for blending or for direct packing. While under some circumstances these bins may be used to store flour for relatively long periods, the storage time is usually short as compared with that for wheat. In the following discussion, "bulk storage" is applied to those systems in which the products of the mill are accumulated in large bins other than those normally used to feed the packers.

General Description

A bulk storage plant for flour consists essentially of: (a) a block of large concrete or steel bins fitted with suitable hoppers; (b) a system of intake conveyors for getting the flour into the bins; (c) a system of feeders and conveyors for getting the flour out of the bins and to the packers; and (d) a system of conveyors and elevators for transferring products from one bin to another, which we shall refer to as the "transfer system." It is convenient to refer to (b) as the "intake side" and to (c) as the

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"discharge side" as they are different in location, design, and capacity.

Although packers are common to all milling plants, the introduction of bulk storage imposes certain modifications in the packing system, and these are so intimately tied up with the planning and operation of the whole bulk storage layout as to warrant special consideration. We shall therefore devote a section of this chapter to the specific problems of packing from the bulk storage system.

In modern mills, the bulk storage section of the plant includes all the handling of the products from the bolters through to the packers. Thus, on the intake side there will be rebolt sifters, recording scales, elevators, horizontal conveyors in the headhouse of the bin section, and perhaps entoleters; while on the discharge side there will be variable speed feeders from the bin hoppers, horizontal conveyors, elevators, rebolt sifters, entoleters, packer feed bins, packers, and the first part of the final conveying systems for the packed products. These are illustrated in Figure 1.

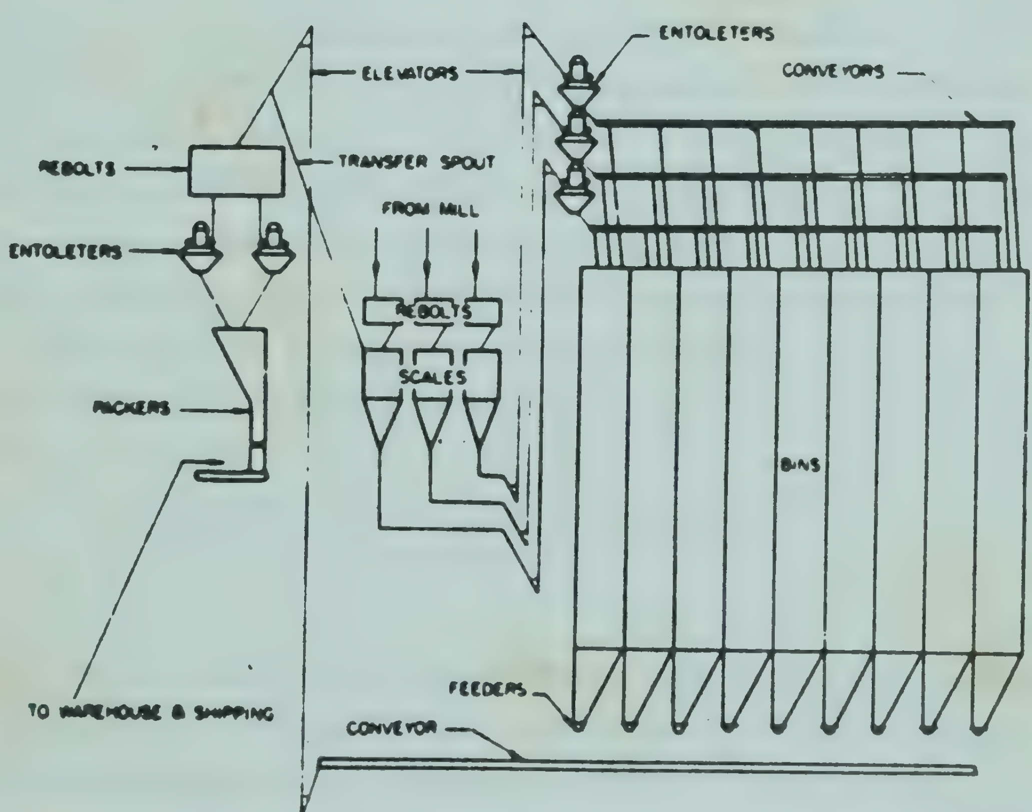

Fig. 1. Schematic flow diagram of a simple bulk-storage plant.

The series of automatic scales that are properly the beginning of the bulk storage system are necessary for accounting purposes since some low-volume streams may accumulate for days or even weeks before being packed off. In the older methods of continuous packing, the rate of packing was about equal to the production rate and hence mill yields and inventory could be readily computed from warehouse tallies. With bulk storage systems there are several ways to find out the amount of stock in the bins, namely, (a) calculate from in and out tallies, (b) take

out the contents and weigh them, and (c) take a sounding and calculate the weight by use of an assumed density of the stock.

In Figure 1, entoleters are shown on both the intake and discharge sides; this represents the ideal arrangement. Often they are used only on one side. This will be discussed in more detail in a later section.

A highly desirable, although not strictly essential, feature of a good bulk storage plant is a transfer system by which material can be shifted from one bin to another. This can be accomplished in a number of ways which will be discussed later in some detail.

General Considerations

Published literature (2, 7, 8, 10) suggests that the early bulk storage plants were built for the purpose of blending flours to increase the uniformity of the product and to make it possible to meet specifications more accurately. In the last few years, however, bulk storage has been considered more as a means of reducing the cost of warehousing, packing, and shipping (6, 9). The reasons for this shift in emphasis are not difficult to find. First, the tremendous increase in the cost of labor has made reduction of handling an economic necessity. Second, a plant designed for blending is of necessity a big plant, and the greatly increased cost of construction has made it necessary to use big plants to the best possible advantage in order to justify the investment in them.

Economic Considerations. The economic justification of a capital expenditure for bulk storage is twofold: labor savings and operational improvements. Labor savings are more readily evaluated and capital outlays, which make them possible, are therefore easier to justify. Nevertheless, there is sometimes greater profit in increasing the total value of products by operational improvements than in decreasing the labor cost of producing them.

By the use of bulk storage a saving in labor can be made in packing operations and, through elimination of warehouse handling, in shipping. Reduction in packing cost occurs in two ways: first, doing all packing on one shift eliminates the extra supervision, laboratory control, and the shift premiums required for night work; second, the introduction of modern high-speed packers reduces the amount of labor required in the packing operation itself.

Reduction in shipping cost may be achieved by delivering the bags from the packers directly to the shipping point (car or truck) by means of chutes or conveyors. This is practical only when the packing is so organized that each product is packed at a rate just sufficient to keep a loading crew fully occupied. In the traditional packing department where all products are packed continuously, the rate of production of all

grades, except those produced in largest volume, is too slow for efficient loading. With bulk storage it is no longer necessary to pack all products simultaneously as it is possible to set up packing lines, using either high-speed or conventional auger packers, with a capacity equal to the efficient shipping rate, and to pack the various products one after another. If the total packing capacity is enough to require more than one shipping crew, then consideration must be given to the desirability of packing two or more products simultaneously rather than in succession. This permits each packing line to operate on the same product for a longer period, and facilitates the prompt completion of mixed loads.

The possibility of savings in packing and shipping by the use of bulk storage depends largely on the efficiency of the operation without bulk storage. Most small mills ship on day shift only, even though they pack continuously. For these mills, daylight packing will permit elimination of most of the warehouse handling of the products packed on the two night shifts. Some large mills, on the other hand, ship on all three shifts and to convert to daylight packing would require a tremendous increase in trackage to permit shipping at the greatly increased rate required. It is doubtful whether the cost of providing such extra trackage, in addition to the extra bins, conveyors, and packing facilities necessary for day-shift packing, could be justified by any saving in labor that might be possible. At the same time, these mills might make a saving in packing and shipping labor by installing bulk storage and using high-speed packers on three shifts, because they could then pack fewer products at a time and handle more efficiently the grades produced in smaller volume.

Operational Advantages. Operational improvements which can be attained by the use of bulk storage include: (a) the elimination of bagging and feeding in of "stuffing" flours; (b) the elimination of rebagging; (c) the ability to accumulate salable lots of flours which are produced at very slow rates, such as second clears, with less risk of their becoming infested than when they are accumulated in a warehouse; (d) improved uniformity of each grade obtained by blending from several bins of the same grade when packing; (e) production of special grades by blending from bins of previously analyzed standard flours; (f) reduction of change-off through longer runs on the same mill mix; and (g) ability to obtain analytical data on finished flours or their components before the flours are packed.

Many of these operational improvements are virtually impossible to evaluate, so it is quite common to build a bulk storage plant designed to permit certain definite labor savings, and then to discover how great a dividend in the form of operational improvement can be obtained

from it. This is not entirely satisfactory, as it may be found that modifications desirable from an operating standpoint, which would have been inexpensive if made during the original construction, are too costly to consider once the plant is built. A more careful consideration, during the design stage, of the possibilities for operational improvement will prove well worth while.

Relation of Plant Size to Desired Functions

A company contemplating bulk storage for the first time is confronted with the problem of deciding how much storage to build. There are plants which hold as little as 2 or 3 days' production and plants which hold over a month's production. All of these may be considered by their owners to be good investments. In general, the operators of any plant will complain that it is too small – that if they had a few more bins, they could do something else which would be an advantage. In the absence of some unusually favorable factor, such as an idle and well-placed building of the right size and type for bulk storage, it will be found that the cost of construction is so great that it is essential to give careful consideration, in advance of detailed design, to the functions to be performed, the savings to be expected from the performance of these functions, and the cost of providing the required facilities.

Preliminary Planning. When functions and their corresponding savings have been listed, the facilities required can be worked out in terms of number of conveying channels to storage, number and size of bins needed, number of conveying channels from storage, and all auxiliary equipment. This may be done either for all functions taken together, which is the largest likely program, or for one important function taken alone, the smallest likely program.

If the largest likely program is worked out first, some pitfalls can be avoided if it is realized that conveying systems and packing and handling equipment must be adequate to deal with any combination of operations that may simultaneously be required; and that the number of bins and the flexibility in their use must be sufficient to meet the needs of all of the desired functions, unless it can be shown that some functions need only be performed at the expense of others. For example, bins needed to permit operation of the mill over a weekend without packing cannot be the same bins as are assigned for the accumulation of slowly produced items unless these items can always be disposed of prior to a weekend run. However, provision for flexibility which will be needed only occasionally may prove unwarranted in view of the additional cost.

Requirements for the largest likely program having been established, the cost of such a program is estimated and checked against the expected

savings. If the prospects are favorable, then this is the desirable program — subject only to the availability of the necessary capital. If the prospects are unfavorable or if maximum investment cannot be made, then the project may be reduced in steps, eliminating the least promising functions first, and making the cost versus savings comparison at each step.

In the alternative approach, the minimum program is studied first and then increased in steps. If the same basic data are used, the two methods will give the same end result.

Whichever method is used, it will be a relatively simple matter to deal with the conveying systems as the required capacities can be readily calculated. As to the auxiliary equipment, it may be established as a matter of policy rather than calculation. But number, size, and flexibility of bins are not so readily established. These points need not be settled in detail in a preliminary study, but some bin size must be assumed for purposes of calculation, and the number of such bins then determined to meet the assumed requirements. For small-quantity items there will be a bin for each item, and for large-quantity items there will be several. There will also be some extra bins to ensure having empty bins available for run changes and possibly for other purposes. For example, records can be kept in better order if a bin is never discharged while it is being filled, but such a procedure requires extra bins for some items which would otherwise need only one each.

Storage Capacity. The minimum plant is usually one designed to allow all the packing to be done in 8 hours per day. This requires a storage section with capacity for 16 hours' production (plus working room) and a packing section capable of packing all the products of 24 hours in 8 hours, or at three times the production rate. A comparatively small additional investment, to increase the storage capacity to 40 hours' production and the packing rate to 3.6 times the production rate, will permit the mill to operate 6 days per week with packing still confined to five 8-hour shifts. With a plant of this size certain operational improvements such as longer mill runs will also be secured. When the mill is operating only 5 days per week it will permit the accumulation of carload lots of small-volume grades in the bins.

To have the plant capable of operating continuously without overtime packing and shipping, the storage capacity must be increased to 64 hours' production and the packing capacity to 4.25 times the production rate. With a plant of this size it should also be possible to reduce warehousing and to ship a large proportion of the production directly from the packers.

If, however, the storage bins are used to maintain a varying inventory, allowing them to fill up when marketing is slow and emptying them

when a favorable market appears, a packing capacity in excess of the minimum required may be needed to meet the peak demands. Considerably greater storage capacity than 64 hours' production may also be wanted. However, the economic justification of such large plants is based on various considerations other than labor savings.

If a plant of large capacity is being planned, thought should be given to the possibility of binning mill streams and doing the blending into grades at the time of packing, instead of at the time of milling. This procedure has several advantages which are very difficult to evaluate, but which have proved profitable for a number of mills.

Bulk Storage of Mill Feeds. This chapter deals with flour storage, but it should be mentioned here that in very recent times successful installations have been made which also include storage of mill feeds in bulk. Though the detailed discussion of this subject is beyond the scope of the present chapter, some reference to the storage of mill feeds will be found in a later section. At this point it is only necessary to say that, in deciding the size of the bulk storage plant, consideration should be given to the possibility of providing for feeds also.

The Bin Block

There are two basic construction materials for large flour bins, i.e., reinforced concrete and sheet steel, and there are several variations in the method of fabrication of each of them. Satisfactory installations have been made with each material. Those who use steel bins claim that they are less likely to give trouble with arching and flushing, while those who use concrete bins point to the saving in space and the insulating property of this material. Steel bins are probably easier to fabricate, and they are more readily installed in existing structures. Furthermore, since the hoppers are invariably made of steel, it is simpler to attach them to steel bins. With the use of concrete, a very high quality of workmanship coupled with good design is essential for the production of satisfactory bins. This combination of skills is not possessed by every contractor who may be willing to undertake construction of a concrete bin block for flour. If competent designers and fabricators for both types of structure are available, the decision can be made on the basis of cost with complete confidence that the chosen system will work satisfactorily.

In general, reinforced concrete is likely to be cheaper for a very large installation where a new building is required, and steel is likely to be cheaper for very small installations, especially if an existing building can be used. For many installations the two materials will be competitive in price. If ground area is severely limited, there is a slight advantage in concrete bins because they are made in rectangular shape and give better

space utilization. This advantage need not be great, however, because the thicker walls of concrete bins, and the air space which is necessary around the bin section to prevent condensation troubles in all but the warmest climates, largely offset the waste space between round bins.

Ventilation of Bins. When a bin is being filled, air must find its way out of the bin at the same rate that flour enters. A simple method of permitting this without blowing out flour is to have a small outlet at the top of the bin which is covered by a dust sock. Another problem which arises, especially if the area above the bins is not kept very warm, is condensation. Flour enters the bins at a relatively high temperature and moisture content, and thus the air above the flour in the bin becomes very humid and, if allowed to cool appreciably, will deposit water which drips back into the bin and forms dough. One method of reducing this difficulty is to ventilate the bins. This is accomplished simply by drawing off a small stream of air continually from each bin. The fresh air introduced from the area above the bins lowers the average humidity of the air in the spaces above the flour to safer levels. Some operators like to apply sufficient suction to the bin while it is being filled to eliminate any back pressure at the inlet spout. This helps to prevent the elevator and conveyor systems from blowing, but this installation is expensive. Equally good results can probably be achieved more cheaply by applying the same suction to the back leg of the elevators.

Size and Number of Bins. Among the first things to be decided in planning a bulk storage plant are the size of the bins and the number to be built. In the basic planning of the system, storage capacity is considered in terms of the hourly productive capacity of the mill; but a certain storage capacity can be achieved in a great number of ways, depending on the size of individual bins chosen. This choice has considerable bearing on the total cost of the project. There are a few operating factors which must be balanced against cost factors in making the decision as to what bin size to use.

To have all the bins the same size, though not essential, has the advantage of providing maximum flexibility, since any bin can be used for any product. Moreover, to reduce the size of some of the bins does not reduce their cost in proportion and, owing to the complication of the design, the effect on the total cost may be quite small. As a rule, then, it will be found desirable to have bins of uniform capacity, and that capacity may well bear some simple relation to the common shipping unit.

The size of an individual bin is subject to fairly definite limitations. In the first place, each bin must have a positive feeder with variable speed drive. This requires an area of approximately 20 sq. ft. for the

smallest sizes, and sets a minimum on the cross-sectional area of bins. Most designers agree that a cross-sectional area of about 60 sq. ft. is as large as is practical, although some of the reasons for setting this limit are not clearly understood or agreed upon. One of the best reasons for limiting the area of a bin is that, because of the steep slope required in hoppers, the cost of the hopper and space wasted in hoppering increase rapidly as the size of bin increases. Other reasons are based on operating difficulties with large bins which have not been satisfactorily explained.

Height of bins is liable to be influenced by the height of adjacent buildings or some other extraneous factor, but in the absence of such restrictions, bins have been built as high as 100 ft. without operating difficulty. This appears to be considered a limiting height. The usual range may be taken to be between 75 and 100 ft.

The density of flour in bulk has been reported (1) as 35 to 40 lb. per cu. ft. Follmer (4) reported that the bins his company had just built had less than the expected capacity, indicating that aeration caused an increase in bulk. Gilmore (5) reported bulk densities as low as 28½ lb. per cu. ft. We have used an average of 33 lb. for estimating purposes. On that basis, the storage capacity of a single bin may vary between about 50,000 and 200,000 lb. The cost per bin for the largest bin will probably not be more than twice the cost of the smallest, so the cost per pound of storage may be twice as much for very small bins as for very large ones. It is therefore desirable to make the bins as large as is compatible with operating efficiency.

Possibly the soundest approach is first to decide the number of bins required to take care of all products plus extras for working room. The number of hours of production these bins would hold if they were all of the maximum practical size should then be determined. If this capacity is more than is considered desirable, the bin size is reduced until the grade most rapidly produced will just fill a bin in the required time. If it is not enough, a sufficient number of bins is added. This will probably give the most economical storage that will operate satisfactorily. Starting the design with a limit on the total volume of the storage is likely to result in smaller bins and more of them, giving less total storage but not necessarily lower cost. An example may serve to clarify this point.

Let us suppose that a mill wishes to provide bulk storage for seven grades of flour produced at the following average rates in sacks per hour:

A	13	E	200
B	50	F	237
C	75	G	250
D	163		

Flour D must go to the storage bins with two different treatments; the change-off flour must also be accommodated; and as the most compli-

cated run produces three grades of flour, three extra bins should be allowed for working room. A minimum of 12 bins is thus required. With bins having a capacity of 2,000 sacks the flour could be accumulated for the following periods:

A	154 hours	D_1	12.3 hours
B	40 hours	E	10 hours
C	26.7 hours	F	8.4 hours
D	12.3 hours	G	8 hours

For minimum daylight packing, storage must be provided for 16 hours' production of each grade being produced plus extra bins for working room and change-off. Grades D, D_1, E, F, and G would each require two bins; but as not more than two of them are made at one time, only two extra bins need be considered. This makes a total requirement of 14 bins.

If a smaller bin size is chosen to cut down the excess capacity provided for the low-volume flours, some saving in bin construction cost will be effected; but this will be more or less completely offset by the cost of extra feeders required for the additional bins for the more rapidly produced grades. Accordingly, the total capital expenditure will probably be about the same as for a plant having a larger total storage capacity.

In some plants, a bin is allocated for change-off flour. But it may be better to provide a bin or bins for that purpose adjacent to the mill rather than in the bulk storage plant. This is a question which must be settled by the particular circumstances.

The Intake System

The conveying system from the mill to the bins must be capable of delivering to a separate storage bin each of the various products made simultaneously by the mill. It must be possible to switch any of the product streams from one bin to another without interrupting the flow. If mill streams are being binned, there will be three streams whose amounts may be 65%, 30%, and 5% of the mill's production. This will require three conveying systems with these capacities. If finished grades are being binned, the products of the mill may consist of one, two, or three grades and provision must be made for handling the various combinations. This is most simply done with three conveying systems with capacities of 100%, 50%, and 10% of the mill production. For most mills the same conveyors would serve for either condition with some alteration in speed.

The first element of the system is the weigh scale which will discharge into a conveyor leading to an elevator that raises the flour above the top of the bins. Automatic dump scales such as are used for this purpose give a pulsating flow, so each must be fitted with a discharge hopper

designed to absorb the surge and enable the conveyor to spread the load over the interval between dumps. It is impractical to adjust the system so precisely that the hopper is just empty when the next dump arrives, so the conveyor must be slightly over capacity and will run empty a portion of the time. It must therefore be a type which can run empty without damage or excessive wear. The hopper should be large enough to avoid danger of the flour in it interfering with the action of the scale. Because of the effect of the scales, it is very desirable when binning grades to blend the mill streams into the desired grades before weighing; otherwise a complicated blending system will be required to ensure that the grades produced contain all the necessary streams in the proper proportions. Usually the elevator spouts into a conveyor, or into one of several conveyors, each of which has several discharge spouts leading to different bins. By setting the proper slide valve, the product can be directed to any one of the bins.

The conveyors above the bins are an infestation hazard and where practical it is preferable to locate the elevator so that it can spout to all the bins it is to serve. This has not been commonly done, but the increasing importance of sanitation may make it more common in future installations. With such an arrangement, the location of an entoleter beneath the elevator discharge will give excellent insect protection to the bins; whereas, with conveyor installations, it is usually considered impractical to have an entoleter for each bin, and locating it ahead of a conveyor does not give complete protection.

The Discharge System

The conveying system from the bins to the packers may take various forms, depending upon the specific requirements. The simplest system is designed to draw flour from any one bin and deliver it to one packer. But it may be desired to draw in approximately equal amounts from two or more bins to increase the uniformity of the product, or to blend the contents of several bins in precise proportions to produce the desired grade from the mill streams in the bins. In other installations, two or more packers may be fed from one conveying or blending system, or two or more complete systems may be required, each system capable of feeding one or more packers. Where two complete systems are required, each may be able to draw from all bins, or each may serve a separate group of bins; or some bins may be served by both discharge systems and others by only one.

Since the bin hopper and feeder are integral parts of this system, they are included in this part of the discussion.

Hoppers. As stated previously, hoppers are almost invariably made

of steel, whatever the choice of bin construction material may be. The shape of the hopper is determined by the shape of the bin and of the inlet of the feeder into which it discharges. The size of the feeder is to some extent determined by the capacity required. For small flows, such as blending systems, wing type feeders which have square inlets are satisfactory. For larger capacities, double screw conveyors, with positive infinitely variable speed reducer drives, are commonly used. These have rectangular inlets whose width is determined by the sizes of screws, and whose length can be varied to fit the bin. One rule of thumb in use is that the area of the feeder inlet should be about 20% of the bin area.

A generally accepted practice is to have no hopper surface inclined less than 70° from horizontal (6). In hoppers from rectangular bins it is common practice to have one perpendicular side opposite each sloping side. This is supposed to eliminate arching. However, hoppers from round steel bins are constructed without vertical sides and operate satisfactorily, so the necessity for vertical sides is open to question. A much more important requirement is that there be no ledge and no sharp corners. One serious defect in some early designs was the practice of bolting the hopper to the inside of the wall. Current practice in concrete bins is to attach the hopper to the bottom of the bin wall in such a manner that there is no ledge at the point of attachment. Great care must be taken to seal this joint to prevent leaks, as it is sometimes subjected to tremendous pressure.

A Swiss patent (3) describes a discharge method for rectangular bins which consists of arranging the bottom of the bin into six hopper outlets, all of which feed into a common circular chamber leading to the conveying system. It is claimed that this gives smooth and uniform outflow.

A recent successful installation on square bins used a transition from square to round to reduce from the size of the bin outlet to that of the feeder opening, and a transition from round to rectangular to produce the proper shape of opening. This form of hopper had the advantage of needing no stiffeners and, when designed with an angle of 65° for the valleys, had a slope of 75° on the sides. The total height between the bin bottom and the feeder was considerably less than would have been required for a conventional hopper.

Feeders. Of the several types of feeders, those most widely used are: the wing type feeder for small flow rates, the double screw feeder for large flow rates, and the traveling belt type weight feeder for precise blending. It is probably most satisfactory to equip each feeder with a separate motor drive, although it is possible to drive a row of feeders from a line shaft using clutches. If double screw feeders are used for

blending, they must be carefully calibrated throughout the operating range for each flour on which they are to be used; for the rate of delivery does not increase in direct ratio as the speed is increased, and the rate of delivery at any speed is different for different flours, depending on the bulk density as well as other factors. This second characteristic applies to wing type feeders, also, and tends to substantiate the claim of Gilmore (5) that for precise blending, weight type feeders are essential.

Control of Flour to Packers. The flour travels from the feeders through the conveyor, up the elevator, along the top conveyor, through the rebolt sifters and entoleters, and into the feed hopper of the packer. If the hopper becomes full, an automatic switch stops the motor driving the feeders; if it becomes empty, another switch starts the feeders and sounds an alarm. The operator adjusts the rate of flow, using the variable speed drive on the feeders to keep the packer hopper partly full, without having the feeders continually going on and off.

If two packers are to be supplied from one conveying system, care must be taken to prevent trouble when one packer does not operate continuously. If each packer has its own sifter, neither sifter will take the full stream, so if one packer hopper fills up, the full stream will overload the other sifter. One solution to this problem is to have the sifters all discharge into a common hopper, or a distributing conveyor, from which the packers draw. Such a system will permit one product to be packed in two different containers simultaneously.

If it is desired to pack two different products at the same time, then a second complete conveying system must be set up to feed the second packing unit. As each bin will usually have only one feeder under it, provision must be made to control each feeder from either conveyor system. It may not be necessary for both conveying systems to serve all bins, but there should be at least some bins served by both systems.

The Transfer System

If the intake and discharge conveyor systems are designed for the highest flexibility, the principal need for a transfer system is to permit weighing up the bins for inventory. However, other circumstances might necessitate transferring flour from one bin to another: e.g., two partly filled bins of the same product might need to be combined in one; or a blend of flour from several bins might be drawn and put into a special bin.

The minimum requirement for transfer is a spout from the elevator on the discharge side to a scale of suitable capacity from which the stream can be fed into the intake side (see Fig. 1). This arrange-

ment has two serious defects: it cannot be used when either the mill is operating or the packers are running, and it can operate at only the capacity of the intake side which is very much lower than the capacity of the discharge side. The addition of a high-capacity conveyor over the bins, and of a separate elevator from the weigh-up scale to this conveyor, permits the transfer system to be operated while the mill is running; and if the discharge side is equipped with two conveyor and elevator systems, transfers may be made while both the mill and some of the packers are operating.

With such a fully independent transfer system it is possible to reduce the complexity and the flexibility of both intake and discharge conveyors and thus achieve considerable reduction in initial cost of the plant. At the same time there is very little increase in operating costs because a product can always be stored in and drawn from any bin whether the intake conveying system that must be used reaches that bin directly or not.

The Packing Department

The first requirement of the packing department is that it shall be capable of packing the total production of the mill during its working hours. In mills without bulk storage, this requires a sufficient number of packers to pack each grade at the maximum average rate at which it is produced. The standard auger packer can be operated by one man at an average rate of 100 to 120 sacks per hour, so any grade produced at a slower rate than this will not keep a packer operating at full capacity. When bulk storage is installed, consideration can be given to packing on day shift only. This requires a packing department capable of packing at an average rate at least three times the mill production rate. To obtain the maximum savings from day-shift packing, the rate of shipping must also be increased to three times the production rate, so that a major portion of the production can be conveyed directly from the packers to the shipping docks.

Packing Rates. If it is desired to grind 6 days per week but pack and ship only 5, the packing and shipping rate must be increased, as noted earlier, to 3.6 times the production rate; and to grind continuously for 7 days per week while still packing and shipping in five shifts requires an average packing rate of 4.25 times the production rate. It should be noted that these figures refer to average rates sustained for a full 8 hours. If the actual operating time of the packers is only 7 hours per shift, the packing rate during the operating period must be correspondingly greater. If the operating conditions are such that the packers have to change frequently from one product to another, the effective packing

time may be much less than 7 hours per shift. Similarly, if trackage is so limited that cars have to be switched into and out of the shipping docks several times per shift, the actual time spent in loading cars may be considerably less than 7 hours per shift, and the actual shipping rate must be correspondingly greater.

Before the development of high-speed packers, the only way to increase the packing rate was to install more packers, and the mill converting to day-shift packing faced the necessity of either building a new packing building or greatly enlarging its existing one. The new packers, however, which are capable of handling up to four times as much flour per machine with very little more floor space, make it possible to convert to day-shift packing in the same space previously used for continuous packing.

Size of Packages. Not many years ago 100-lb. sacks of cotton or jute were used for most of the flour produced in America. More recently paper has become increasingly important until now its use about equals that of cotton. Jute is seldom used in domestic trade but is still fairly popular for export markets. Another important development is the increasing use of smaller packages which are almost exclusively paper. Packages of 25 lb. and smaller are not filled on regular packers but are handled on entirely different machinery. One such unit can pack and seal approximately one thousand 10-lb. packages per hour. This will handle the same amount of flour as an auger packer, but requires three operators, two of whom may be women. Although the total amount of flour sold in small packages is relatively small, and many mills do not pack any small packages, some mills may pack most of their production in this manner. These mills have much greater difficulty in adjusting their packing operations to fluctuations in the ratio of large to small packages in demand, for the labor requirements are so much greater for small packages.

A mill with a packing capacity of 4.25 times its production rate should be able to pack without overtime even when the mill runs continuously; but unless the capacity is properly distributed between large and small packages and between paper and cotton in large sacks, it may be necessary to run part of the packing department overtime to meet a heavy demand for a particular size or type of package, while the rest of the packers are idle. For this reason, a mill with a very diverse trade, which is subject to wide fluctuations in demand, is well advised to install packing equipment as versatile as possible, and may find that the total packing capacity which ensures that no overtime will be required is considerably more than 4.25 times the production rate, but that it is seldom all used at once. If the bins are used to maintain a varying

inventory, the packing capacity will be determined by the maximum rate at which the sales department wishes to ship. This may be much greater than 4.25 times the production rate.

High-Speed Packers. The first high-speed packer to be developed was the Bates valve bag packer. This is an excellent machine which has been proven by many years of service. Its main limitation is that it can only be used for filling paper bags, and the special patented valve bag must be used. If a mill has sufficient demand for flour in paper bags to keep one of these machines busy continuously it is probably still the most economical way to pack. More recently two other types of high-speed packers have been developed which can handle both cotton bags and open-mouth paper bags. These more versatile machines are still being improved, but up to the present neither will operate equally well with cotton and paper, one being better on cotton and the other better on paper. However, a mill with a fluctuating demand for both types of bag should consider one of these machines.

Additional Packing Problems. Although some mills with bulk storage may not have high-speed packers, they will nevertheless want to reduce the number of grades being packed simultaneously and thus simplify the conveying system from bins to packers and increase packing and shipping efficiency. The simplest way is to pack one product at a time. This requires only one system of conveyors from the bins to the packers. If there are separate packers for paper and cotton, then it may sometimes be desirable to pack the same product in the two different containers at the same time. If this is done, there will be two separate product streams from the packers to the warehouse and loading docks. It is probable that the two streams will be wanted at different destinations; so there must be either two separate conveying systems from the packers, or a merging device to put bags from different sources on one conveyor and a sorting station somewhere along the route to separate the cotton from the paper. If some of the packers can pack either paper or cotton, and there are separate conveyors from the packers, then these packers must have a means of delivering to either conveyor.

Mills that pack small packages usually pack only one or two grades in this manner, so there must be provision for supplying the small package line with the proper grade when the main packing department is packing other grades. This may be done by having a special conveying system from the bulk bins for this unit, or by having auxiliary storage bins which are filled when the grade is being produced or when it is being packed, and from which the small package line draws.

As one high-speed packer should be adequate for a 2,000-sack mill,

only the larger mills need consider the problem of packing more than one product at a time when high-speed packers are used. Here the deciding factor is shipping facilities. One high-speed packer will keep a shipping crew reasonably busy, but the stream from two such packers working on the same product can be handled by a crew less than twice as large. If most of the mill's production is shipped in straight carload lots, it is most economical to pack one product at a time. If, on the other hand, most shipments are made up of two or more products, the large mill should be able to pack at least two products simultaneously—unless it has sufficient trackage to spot all cars for a day's shipping at one time. Under the latter conditions it can load the different products into all cars in sequence and dispatch them all at the end of the shift.

Sanitation

Rebolting of flour through 9xx silk has long been the accepted method of removing all insect life from flour, and the method is theoretically sound. However, the difficulty of maintaining all sieves in perfect condition makes it impossible to prevent the occasional leak. This is not too serious when the rebolting is done immediately before packing, as any living insect getting through the leak will be immediately packed and shipped and will affect only a small amount of flour. If the flour is held for any appreciable time in a bin, however, the insects have a chance to establish a breeding spot in the bin, and a very minor leak in the rebolts may cause infestation of a large amount of flour. Should a bin become infested, the only sure way of correcting the situation is to empty the bin completely and treat it with a penetrating fumigant such as methyl bromide. The flour removed can be fumigated in the sacks.

The soundest course is to prevent infestation by the use of the entoleter impact machine. This machine does not require careful maintenance to keep it at top efficiency and is therefore eminently suited for protecting storage bins from insect contamination. It does not replace rebolting for removal of other foreign material, but it will ensure that occasional leaks through the rebolts will not cause infestation in the bins. The cost of putting an entoleter on the inlet of each bin is so high as to be considered impractical in most cases and the usual thing is to place an entoleter just ahead of each of the conveyors above the bins. This gives less protection, but at much less cost. A suggested improvement would be to place an entoleter so that the flour passing through it can be spouted to any one of a group of 4, 8, or 16 bins. This would mean elevating the stock high enough to spout into these entoleters, but because conveyors above the bins would be elimi-

nated entirely, the possibility of infestation would be greatly reduced.

Rebolting has always been done immediately before packaging and this is probably desirable. However, it does not seem necessary to rebolt through very fine cloth more than once. If the flour is rebolted through 9xx as it leaves the mill, any contamination it may receive subsequently, other than insects' eggs, will be removed on a coarse screen such as 38 wire. The bolting capacity of a sifter clothed with 38 wire is almost three times as great as when clothed with 9xx. It is cheaper to leave intact the original rebolt installation in the mill and install on the discharge side a second rebolt system clothed with 38 wire, than it is to increase the rebolting capacity sufficiently to rebolt through 9xx at a packing rate which may be more than four times the production rate.

Effective protection can be obtained with entoleters at the entrance to each bin and rebolt sifters clothed with 9xx silk followed by entoleters over each packer. A somewhat cheaper way to get as good or better protection would include: rebolt sifters clothed with 9xx at the mill, entoleters at the inlet to each bin, rebolt sifters clothed with 38 wire followed by entoleters over each packer. The entoleters over the packers are probably the least essential in this system, although they are most often installed in this location. If the bins are kept free of insect life and reasonable housekeeping is maintained in the packing department, there should be no need for entoleters at the packers. However, by the same reasoning, if the mill is kept free from insect life there is no need for entoleters at the inlets of the bins. Each added precaution is merely insurance against serious consequences resulting from conditions which are not normally expected to occur.

Bulk Storage of Mill Feeds

Although the discussion of bulk storage has been confined to flour, and rightly so because it is the principal product of wheat milling, it is recognized that the mill feeds — bran, shorts, and middlings — can also be stored in bulk. Indeed, in a milling system designed for packing a 24-hour production in 8 hours, bulk storage must be provided for all the products of the mill.

There are some special considerations in the bulk storage of mill feeds that almost warrant a separate treatise. However, as many of the considerations are common to both flour and feeds, it may suffice to point out here only a few of the specific differences in order to emphasize the fact that additional factors must be assessed when extension of the bulk storage to embrace all the other products of the mill is being planned.

The problems with feeds are, in one way, simpler than those of flour, and, in another, more complex. In the first place there are fewer products; they are not usually blended; and when packed they are almost universally packed in 100-lb. bags. Furthermore, as they represent only about 25% by weight of the total mill products (about 33% by volume), the rate of production is relatively low and is fairly constant. These factors tend to reduce the difficulty of proper planning for space.

However, the methods of disposing of the feeds are more varied in one sense than with flour, and this imposes the need for detailed consideration of the kind and amount of storage to be provided. Furthermore, owing to the nature of these products, difficulties with compacting in the bins, with discharge, and with conveying, create problems for which completely satisfactory solutions have not yet been obtained.

Mill feeds may be disposed of in one or more of three different ways, namely: in 100-lb. bags, in bulk cars, and by direct continuous transfer to an adjacent formula-feed mixing plant where they are received into appropriate bins. Frequently all three means of egress from the mill are used.

For packing-off the feeds in bags, the problems are not any more complex than for flour, except for the behavior of these soft-textured products in large bins. It is often the practice to pack feeds throughout the 24 hours as the packing crew needed is small. A 6,000-cwt. mill would produce feeds at the rate of about 85 cwt. per hour, an amount that could be handled easily by a minimum crew. If, however, part of the feeds output is being loaded in bulk cars or is being diverted to a formula feed plant, the small amount to be packed in bags scarcely warrants the cost of keeping the packing crew on during the two night shifts and it becomes relatively expensive to do so. Hence, under these circumstances, bulk storage with only daylight packing would be justified economically.

Another consideration is that of loading cars "off the line," either in bulk or in bags. When drawn from bulk storage, the feeds can be loaded on cars at the rate of 1 to 2 hours per car, but the full output of bran or shorts from a 6,000-cwt. mill would require 20–24 hours to make up a carload. It is obvious that loading straight cars of feeds from bulk storage is more economical of labor and avoids long tie-up of carloading spots.

On these grounds, some mills might be able to justify bulk storage for mill feeds, even though they might not be able to justify it for flour.

High-speed packers for feeds, designed to handle 200 to 250 bags

per hour, are available to the industry, but there is scarcely a plant on this continent that could keep one of these packers running steadily off the line of production. Only with adequate bulk storage could the installation of such packers for feeds be justified.

We have pointed out some of the general problems that must be studied when considering bulk storage for feeds. There are many other problems of bin discharge, conveying, etc., but they would require lengthy discussion beyond the limits of this chapter.

Problems Arising from Bulk Storage

We have dealt thus far with considerations pertinent to planning, installing, and operating a bulk storage system for flour. The treatment of the subject has, of necessity, been generalized, and would perhaps fit best into the planning of complete new units. It is fully realized that most of the bulk storage plants erected in the next few years will be adjuncts to existing flour mills, each of which will be unique in its layout, capacity, and operation. The introduction of bulk storage of flour into an existing mill brings in its train a number of technical and operating problems not normally encountered in conventional mills, particularly in the smaller ones. These problems cannot be dealt with in any detailed manner because they vary with each mill. However, this chapter would not be complete without a survey of the difficulties to be watched for in related operations once the bulk storage has been installed.

As these problems arise from the introduction of new operations and from the acceleration or bunching of otherwise familiar operations, they must each be studied individually. Partial or complete solutions have been found for some of them, but no attempt will be made here to describe these solutions or to judge the merits of various methods of solution. Usually, a recognition of the problem will provide a lead to its solution.

Bulk storage itself is a new operation that presents problems not encountered before. While there may be a tendency to consider bulk storage bins merely as extensions of the packer hoppers, this view is not correct for various reasons. Arching in a hopper can be solved with a mallet, but arching in a large bin may require elaborate means of correction. The collapse of arched flour will not destroy a packing hopper, but it can easily cause serious damage to a bin that is incorrectly designed. Flushing in a packing hopper occurs right in front of the operator and he can stop it immediately, but flushing through a feeder in a large bin will choke the equipment following the feeder.

Carry-over of stock in a distributing screw conveyor can easily be

serious where this method is used to deliver flour to a group of storage bins.

Condensation will give little trouble in a conventional mill where warm flour is handled in warm surroundings until it is safely in the sack; but with bulk storage, which may or may not be adequately protected, the flour can misbehave in many ways due to condensation, and the nature of the trouble may not always be too apparent. For example, arching may occur in a bin which has never arched before if the temperature has dropped just enough to cause condensation at critical points.

Besides the act of storage itself, other new operations may be introduced for the first time with bulk storage. Automatic scales are normally provided to weigh the streams to storage. Besides weighing the streams, the scales will interrupt and bunch them, causing irregular flow which must be allowed for in the design of the conveying system beyond the scales.

Blending of flour streams, if it is done, will be a new operation. There are more pitfalls in the blending of flour than are likely to be encountered in the blending of other materials. The accuracy of conventional blending equipment depends on a number of variable conditions which need to be understood and allowed for, as follows:

1. Accuracy of calibration.
2. Inherent differences in different flours.
3. Linearity of feeder response.
4. Effect of pressure variations on feeder response, and frequency and magnitude of pressure variations.
5. Variations in flour density.
6. Existence and effectiveness of alarms, interlocks, and other protective devices.
7. The human element.

Blending difficulties may occur even if blending is not a normal operation, as, in the absence of proper interlocks, the discharge system may accidentally draw from more than one bin at a time, thus mixing flours inadvertently.

In some plants, proper use of bulk storage may make it necessary to use more than one high-speed packer on one stream of flour. There is nothing unusual in the use of more than one conventional auger packer on one stream and the balancing of the loads is not difficult. The hopper over the packer is large in relation to the packing rate and if one packer stops there is plenty of time to adjust the stream rate, speed up the other packers, or switch in a spare packer. But with high-speed packers the hopper may contain only a few minutes' supply and

if one packer is in trouble there will be a choke unless it is prevented automatically. Ordinarily a bin level indicator is provided on each hopper to indicate when it is too full, or better, to stop the feed when this occurs. However, the feed is stopped to all packers, and, before production can be resumed, the feed rate must be adjusted to suit the remaining packers and the slide controlling the supply to the defective packer must be closed. All of this must be done manually and takes time. It has to be done again in reverse as soon as the defective packer is ready to restart. Moreover, as most delays are of unknown duration when they begin, the operators will, if left to themselves, let the whole system remain idle during the delay, with consequent unnecessary loss of production.

It is common practice to have one rebolt sifter above the hopper of each high-speed packer and to supply these sifters from a common conveyor. If instead of this, all the rebolt sifters discharge into a common conveyor from which each packer hopper is fed, the problem is greatly simplified. The system will stop and start more often since the feed rate will have to exceed the packing rate by some small margin, but no harm will be done. But with the rebolt sifters designed to carry only normal operating loads, stopping one of them will automatically overload the remainder and a choke inevitably results.

Of the problems that arise from the acceleration and grouping of operations, the most serious may well be a failure to grasp just how much acceleration is involved. As equipment gets larger it becomes expensive to "overdesign," and large equipment is therefore usually designed close to expected requirements and it may be impossible as well as undesirable to overload it. Thus, a 2-hour interruption of packing in 24 hours requires a 10% speed-up to catch up, but a 2-hour interruption in an 8-hour day requires a 33% speed-up to catch up in one day. The extra capacity needed to take care of emergencies of this kind must be allowed for in the design of all of the equipment in the discharge system — feeders, conveyors, elevators, sifters, and packers. If packers are of the conventional auger type they have a reserve capacity which can be exploited by a skillful operator; but high-speed packers have a maximum speed which is in effect the normal operating speed, and there is no inherent extra capacity.

The delivery of sacks from the packing room to the warehouse or to cars at three or four times the previous rate may disrupt the normal method of handling at the receiving end, since only a limited number of men can be usefully employed at a conventional receiving table. Any irregularity in the rate of the stream, or any interruptions, will cause further trouble, and troubles of this kind tend to be cumulative.

If the stream is too large or if it is required at more than one destination at once, some form of splitting or sorting will be used. In the conventional mill, the sorting is done either at the sewing machine, usually by the sewing machine operator, or at a sorting table. With individual sewing machines, with or without high-speed packers, there is no longer a sewing position where this function can be performed, and with a large stream, a sorting table may be practical. The introduction of bulk storage may therefore bring with it the need for entirely new methods of sorting or splitting of streams of bags.

In some cases the problem is reversed, and there is a merging problem rather than a splitting problem, or the two problems may occur in the same plant. Merging is needed when the production from more than one packer is required at one destination or must travel a common route. In the conventional mill using auger packers with a common sewing machine, the merging is taken care of by the individual operators who select a suitable place on the sewing belt to deposit each bag. When individual sewing machines are installed, there is no longer any need for the operators to handle the bags to get them away, and to have them lift the bags onto a common belt, just to merge their production, becomes a waste of labor. Mechanical merging devices are then required.

The packing and handling of short runs and of small packages may become unexpectedly complicated when bulk storage is introduced. At higher packing speeds, a short run becomes a shorter run, and the time of changing runs and the amount of mixed flour which must be set aside become much more significant. Small packages are handled on special machinery which operates at a speed far below the normal packing rate in terms of pounds of flour per hour. Allowance must therefore be made for the time the discharge system is to be operated at this reduced rate, unless a separate discharge system is used for small packages.

Of the operating problems brought by bulk storage, probably the only one that is new in kind rather than in degree is that of production records. As soon as some production is binned and not packed, mill production and packing room production are no longer the same thing. Automatic scales on each stream will give mill production, and packer tallies will give packing room production. Inevitably there will be a gain or loss over a period which must become known, and this can only be done by either running the bins out or taking an inventory of the bins. Accountants tend to be skeptical of bin soundings and even of weigh-ups and will prefer to have bins run out, which of course defeats the object of having the bins. Weigh-ups are expensive, both in

the equipment and in the time required, and even soundings take time which might better be employed otherwise. Much trouble can be avoided if the methods for obtaining the required records are decided in advance of construction and the equipment arranged accordingly.

Conclusion

We have enumerated in this chapter most of the considerations necessary for careful and intelligent planning of bulk storage for flour. Recognizing that each milling plant is unique in its physical aspects and in its operation, we have deliberately avoided specific details which can best be worked out on the actual job. For management, engineering, and operating departments, this chapter should serve to point out the many factors that must be thoroughly considered in planning the installation of bulk storage facilities for flour. Going beyond the actual bulk storage unit itself, we have dealt with some problems that may arise as consequences of such installation.

The many advantages of bulk storage of flour can be fully realized only if all the factors involved are known and are thoroughly studied before a final plan is accepted. Most of the difficulties usually attendant on the breaking in of a new bulk storage system could be avoided, or at least reduced to small magnitude, if the project were carefully planned with full recognition of all the effects the system may have on the milling plant as a whole.

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CHAPTER XI

Packaging and Storage of Cereal Products

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Many readers of this chapter on packaging will have two questions in their minds: first, why packaging was included in a monograph on cereal products; and secondly, why this chapter was not more detailed and precise.

The answer to the first question is not entirely known to the writer because he had no part in the deliberations of the editorial group that organized this work. However, he commends their understanding of the importance of packaging for every kind of product in our present economy. The unit of sale is *the product* and *the package*. A product can be carefully formulated, skillfully produced, and cleverly promoted, but if it is not protectively and conveniently packaged, it cannot achieve success.

The second question will be asked particularly by cereal chemists who will appreciate that the chapter on packaging is not on the same scientific level as many of the others. The answer to this question is properly the sole responsibility of the author who would like to treat it in two parts. First, there is no science of packaging. For many years packaging has been moving towards a technical basis, but, as much remains to be done before this goal is reached, it is not possible to present the subject in the rigorous manner expected in a monograph of this kind. The remaining reason has to do with the very practical matter of space limitations. If the subject were completely developed, it would require many times the allotted space and would probably confuse rather than inform. There are such large numbers and varieties of cereal products, each packaged in many different ways, that elaborate discussion of them would be impossible. The author's approach has been to cover the fundamentals, describe typical materials and package forms, and show how typical cereal products are packaged. This chapter will not make the reader into a packaging expert, but it should develop an appreciation of the subject and an understanding of the problems peculiar to packaging.

General Considerations

The problems of packaging cereals and cereal products and the methods of developing packages for them are similar to those met when dealing with other products. Cereals have certain properties and requirements which demand special consideration or emphasis, but the general technics, theory, and engineering approach are the same as for any other group of products or commodities.

An engineering approach is the only sure means of developing a proper and efficient package for a standard article or for a new and specialized cereal product. This approach, together with judgment and experience, will ensure the preservation of the product at the lowest package cost commensurate with the merchandising and product requirements.

Cereal products are generally characterized as having good stability, moderate densities, and low costs. These three characteristics greatly influence the problem of packaging as related to both cost and preservation. However, many cereal products have been modified by elaborate processing, many additives, or both. Such products, though predominantly of a cereal nature, are unstable, of low density, and of higher cost. Apparently trivial differences in formulation or in processing can change the preservation requirement.

Widely ranging demands in merchandising and distribution, which affect preservation by varying the time and conditions of exposure and storage, confront the cereal industry with further problems in packaging requirements. Complication is added by the type of machinery possessed, and by knowledge of consumer habits, both of which limit free choice of forms. Shortages of supplies or other difficulties may necessitate changes in package specifications. Differences in raw materials or merchandising methods are sometimes responsible for variations in the packages used by different manufacturers of the same type of product.

The results of these conditions can be seen in the large variety of packages and materials used today for the packaging of cereals and cereal products. In the following discussion, however, only typical products can be discussed, only basic packaging needs outlined, and only a general description given of commercial packages.

Though packaging must be considered mainly as a means of preservation and distribution, other factors are also involved. In the United States where self-service is a dominant method of merchandising, the package must be attractive and must also carry the trade-mark to the customer. To encourage repeat sales it must also be designed with the ultimate use in mind: it must be convenient in size, and easy to open

and reclose. However, since a package has no intrinsic value to the final user, its cost must be kept as low as possible and in some reasonable relationship to the cost of the finished product. These conditions impose restrictions on the packaging of many cereals and cereal products because of their commodity-like character and their low selling price. Cost limitations are usually less stringent on specialty products and on nationally advertised trade-marked brands because these must have better packaging for preservation, distribution, and point-of-sales appeal.

Packaging of all products is increasing at the expense of bulk handling for many compelling reasons. Packages provide better preservation for long-term storage and shipment and make more economical use of warehouse space. They save labor in both distribution and selling. They lend themselves to the distribution of an identified product which can be effectively advertised. And finally, by the economy with which they provide for adequate preservation, they serve to meet the growing customer demand for "perfect" products.

Many of these considerations apply to retail units for home use, but some apply also to industrial or institutional units. The larger units generally move through distribution channels in less time than small units, and preservation is less of a problem. Lower grade packaging materials can often be used for larger sizes, provided that they have the required strength and durability, qualities which become of greater importance as size increases. Also, for large units little extra cost is needed for decoration beyond that required to establish the brand, source, and composition of the product.

Package Engineering

Many cereal products are merchandised in packages which are superficially similar in shape, size, and materials employed, but the possible combinations of materials and package types are so great that packaging is a confusing subject to those who have a limited knowledge of its problems and who do not understand its terminology (16). In general, there are no universally accepted principles for package engineering, few standardized tests for materials or packages, and very few specifications for quality or performance. This, coupled with the lack of data on the packaging characteristics of products, leaves much to judgment and experience. Though many companies have their own packaging engineers, tests, and specifications, a common technical basis for solving packaging problems does not exist at present. It is generally conceded, however, that package engineering must be based on a consideration of factors that can be grouped under the following headings: packaging characteristics of the product; merchandising and handling

factors; and the physical and preservation functions of the package and its materials of construction. These three topics are discussed in the following subsections.

Packaging Characteristics of the Product

With a knowledge of the formulation of the product, the factors affecting its packaging characteristics (17) can all be determined in the laboratory by various tests. But although the packaging characteristics of a product are dependent upon formulation, processing, and chemical composition, they are often not predictable from even a complete knowledge of these things and must be determined empirically by special means. Thus special tests, of the nature of performance trials, will usually be needed to establish the packaging qualities of a product.

Some of the product properties which must be known are given in the following subsections.

Equilibrium Humidity. This is the relative humidity at which a product neither gains nor loses moisture (2, 9); it is usually measured at or slightly above the typical storage temperature. The lower the value of the equilibrium humidity of a product the more likely it is to gain moisture from the atmosphere. Conversely, as the equilibrium humidity values rise above normal atmospheric humidities, the products will tend to lose moisture.

Cereal products like normal white flours of about 13% moisture content have equilibrium values in the range of 65% R.H. and so do not need package protection against moisture migration since the vapor pressure differentials between product and atmosphere are usually small.

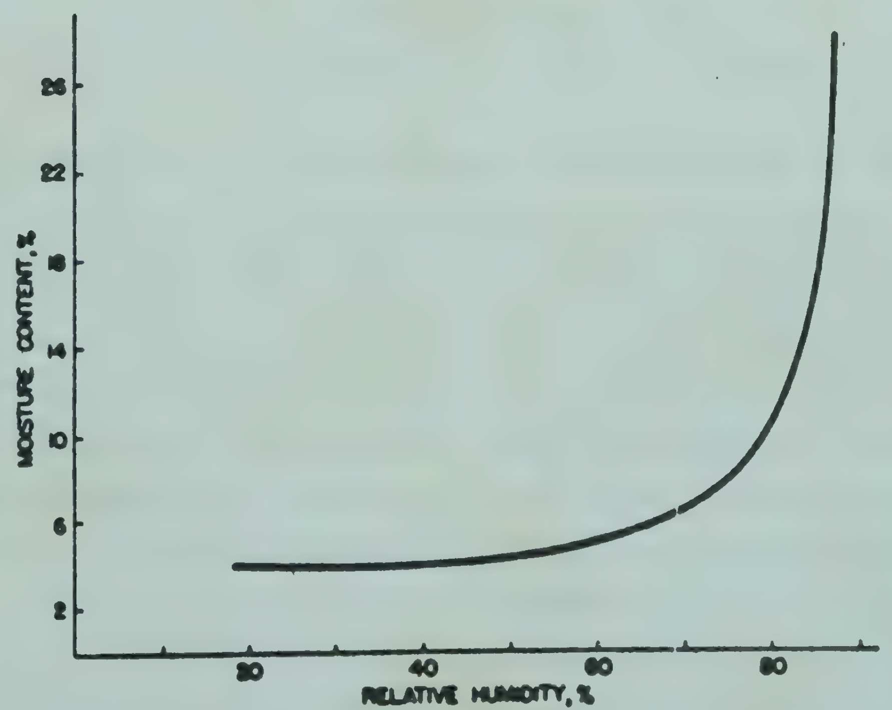

Fig. 1. The relation between the equilibrium moisture content of a white cake mix and the relative humidity of the atmosphere.

However, cereal products that have been heat processed or mixed with some types of additives may have values in the range of 30% R.H. An example of a product with a low equilibrium humidity is the white cake mix for which the data plotted in Figure 1 were obtained. Such products will require a careful choice of moisture barriers and well-sealed packages to prevent excessive moisture pickup in storage.

The determination of the equilibrium value of a new product is most important as a guide to the materials and the construction of the package (3).

Causes of Product Deterioration. Gain or loss of moisture generally causes some deterioration of the product. The value of the equilibrium humidity shows the humidity at which the product starts to gain or lose moisture, but it is also necessary to know how much the moisture content can change without making the product unusable or unsalable. In other words, the capacity of a product to lose or gain moisture without deterioration is an extremely important fact for the package designer to know, since it helps to determine the required degree of moisture-proofness of the package.

An empirical expression for the relationship between equilibrium humidity and capacity to lose or gain moisture can be developed in the following manner, provided that the rate of water vapor transfer through a package barrier is assumed to be proportional to the water vapor pressure difference existing across the barrier. Actually this assumption is not valid for some barrier materials or for some levels of humidity or differences in vapor pressure.

In mathematical symbols, the assumption may be written:

$$\frac{dW}{dt} = B\,(P_a - P_p) \qquad (1)$$

where W = mass of water vapor transmitted;

$\frac{dW}{dt}$ = rate of transmission of water vapor in units of mass per package per day;
P_a = water vapor pressure of the atmosphere;
P_p = water vapor pressure established by the product inside the package;
B = a constant of proportionality which must be determined experimentally for the package material and package type in question.

The value of B will probably be constant only for a limited range of temperature and exterior humidity, and it will be dependent upon the water vapor transmission rate of the package barrier and the efficiency of its use in the forming and sealing of the package.

Expression (1) when integrated becomes

$$W = B\,(P_a - P_p)t \qquad (2)$$

and the loss or gain, W, can be calculated for a given time t. If m_1 is the initial moisture content, the moisture content m_2 after an elapsed time t will be:

$$m_2 = \frac{\frac{m_1 M}{100} + W}{M + W} \times 100 \qquad (3)$$

where M is the initial total weight of the package content.

If P_p is greater than P_a, their difference will be negative and W will also be negative; i.e., the package will lose weight by losing moisture. In any case, the package must be designed to hold the values for m_2 within the safe range.

These equations are sometimes useful in estimating the effects of storage under carefully controlled laboratory conditions, but they are not a reliable basis for predicting shelf life under actual field conditions, because of the effects of large changes in the ambient temperatures and humidities. Oswin (15) and others have attempted to estimate shelf life using only a few constants derived from laboratory studies. However, all such attempts require many assumptions, most of which are valid only for simple products or limited ranges of atmospheric conditions. The equations are given here only to emphasize the fact that in considering the changes in the moisture content of a packaged product with time, the product, the package, and the atmospheric conditions must all be taken into account.

Many cereal products are susceptible to the development of rancidity, and it is necessary to know the degree of this susceptibility and its effects on the acceptability of the stored products. Suitable package construction and specification will ensure that the package does not catalyze the oxidation of absorbed fat (19) and will help to prevent the development of rancidity by excluding light or oxygen or both; or, if rancidity is unavoidable, will mitigate the effects by allowing rancid odors to escape. At present, however, only metal cans or glass jars can be made reliably oxygen-tight.

Obviously no package can protect a product from changes of temperature, but if a product must be stored and handled within a specific temperature range then the package must be designed to perform under those conditions.

Many products carry flavors or other additives that are volatile at the temperature of storage and handling. The loss of these components can change the character and acceptability of the product. It is not possible to determine the specific permeability of package materials to aromatic mixtures, although such data for pure gases are available. However, well-sealed sample packages can be formed from a variety of materials, and storage tests will indicate those which are most effective in keeping the loss of volatiles to an acceptable level.

Freeness of Fats. It is necessary to know if the fat (this includes all

fats, oils, etc., whether naturally occurring or additives) carried by a product is free to migrate to the surface and so coat or be absorbed by the package materials in contact with the product (13). The freeness of the fats has no direct relationship to the amount of fats present or their composition, although the higher the fat content and lower its melting point the more probable it is that greaseproofness will be needed. There is no official method available for measuring the freeness of fats, but a generally used test consists of placing the product on a piece of soft, white, unsized paper and holding it for 24 hours at 90° to 100°F. It may be necessary to place a small weight on the sample to ensure contact with the paper. An examination of the paper will show the degree of fat staining. If only a few spots of staining show, then it may not be necessary to use packaging material of a greaseproof type. However, if the test paper shows extensive staining, the package materials in contact with the product must serve as a barrier to keep the fats from appearing on the surface of the package.

With marginal freeness of the fats the package materials in contact with the product may be allowed to absorb the small amounts of fats, but care must be taken to select grades and types of materials that will not catalyze the breakdown of the absorbed fat (19). This problem is particularly acute with many kinds of baked goods in which the shortening used is degraded by the baking process or the product picks up fats used to coat the baking pans.

Some cereal products, either because they contain a sufficiently high percentage of added fats or because they have been cooked in fats, require the use of truly greaseproof materials as well as tight seals and closures to prevent fat migration. Among such greaseproof materials are glassine, parchment paper, cellophane, some of the plastic films, and special coatings on paper. With most cereal products, however, a greaseproof package is unnecessary.

Physical Properties. Certain of the physical properties of the product must be known to the packaging engineer. A partial list of such physical properties would include: bulk density, abrasiveness, fineness, flow characteristics, brittleness, etc. Some unusual characteristics may require special consideration in the design of a package. The package is responsible for the delivery of its contents without losses and without excessive physical breakdown. Also the contents should not sift between the package components, should not abrade the package materials, and should not distort the shape of the package.

It will not be possible to measure or establish values for many of the physical properties that must be considered, but laboratory package tests, together with trial shipments, should establish and confirm the

general suitability of the package, its materials, and coatings. It is particularly important that in such tests both the package and the filled shipping case (freshly packed as well as after storage) be exposed to compression and rough handling.

Chemical Properties. This is a general heading to cover many possible interactions between the product and the package materials that are not covered under the previous heading of "Physical Properties."

Cereal products and their additives can react with certain types of package materials to cause some form of deterioration of the product, of the package material, or of both. Thus some coatings or plastic films may be softened and their physical and protective properties degraded by fatty substances; cellophane and glassine may become brittle by loss of moisture caused by the dehydrating action of cereal products of very low moisture content; plasticizers, resins, and ink colors may be affected by volatile components or the products of oxidation; and products may absorb some of the volatiles from the package with resulting off-flavors and undesirable taste.

These cases are typical of the kind of effects that must be considered under this heading. There are no test procedures to establish or measure these interactions and they can best be guarded against by accelerated and long-term tests which duplicate as nearly as possible the conditions to be encountered by commercial shipments.

Most of the qualitative requirements of the package and its materials can be established from a knowledge of the requirements of the product for its preservation, coupled with a knowledge of the interaction between product and package materials. But for a complete description of the required package qualities something more than a knowledge of the packaging characteristics of the product is needed, and the second group of factors—those dependent upon merchandising and handling methods—must now be considered.

Merchandising and Handling Factors

Information about the factors involved in merchandising and handling should make it possible to fix the size of the package and its type, the physical requirements, such as stiffness, and the specifications for the decorative and printing requirements. Knowledge of these factors should also decide questions regarding the use of such conveniences as pouring spouts, opening means, etc., and, most important, provide data as to the length of time the product will remain in the various channels of distribution, particularly as a single unit at the point of sale and at the point of use. This last requirement, the time factor, together with the climate of the area of distribution, obviously will have a bearing on the degree of preservation required, and so affect the choice of materials.

Another consideration concerns the type of failure which is least unacceptable to the sales department. Many products can become unsalable or unusable in several different ways resulting from different causes. The choice of package material can, in some cases, control or influence these causes of failure, and it then becomes important to decide the kind of product deterioration which is least objectionable. When this is done, the extent of deterioration that can be permitted must be established as a guide to the packaging engineer in evaluating various materials and packages.

It is apparent that most of the information required must be based upon estimates or opinion. It cannot rest on the more solid foundation of laboratory data often available for studies of the other factors discussed in this section. It is probably safe to say that almost no company has valid and reliable information on most of the factors involved in merchandising and handling. But in most cases, some guidance in the packaging of a new product is provided by experience with established products of similiar composition or having some similarity of properties. With an entirely new product a great deal of uncertainty must necessarily occur and the general rule is to make estimates sufficiently pessimistic so as to result in a considerable degree of overprotection by the package. It is better to overprotect a new product initially, and then to reduce the cost and degree of protection with time and experience, than to have serious failures on introductory shipments.

Certain exact data can emerge from a consideration of the factors under discussion. For example, the decision as to the size of the package unit, in terms of both weight and dimensions, will have a considerable effect upon the final choice of the materials and perhaps on the type of the package. A package carrying 1 oz. of product will have much more surface exposure per unit of weight than a 1-lb. package. Since moisture transmission into a package is a direct function of the surface area, the package area per unit of weight can have an effect on cost and shelf life. This fact is so important, so little appreciated, and yet so capable of some control, that it will be elaborated upon.

For example, 1 oz. of a dry cereal product can be packaged either in a folding carton 1 by 2 by 3 in. or in a flat envelope 4 by 5 in. The carton will have a surface area of 22 sq. in. and the envelope 40 sq. in. For the same shelf life, assuming comparable tightness of seals and seams, the envelope material must possess twice the degree of moisture protection, i.e., one-half the value of the water vapor transmission rate.

Functions of the Package

The factors discussed in this subsection concern the function of the package material and the package. By combining the requirements of

the product and the requirements for satisfactory merchandising and handling (discussed in the two preceding subsections) it becomes possible to decide qualitatively and quantitatively the properties and functions required of the package material and the package. It must be kept in mind that the word "function" can also be used to cover certain of the decorative features as well as physical and preservation characteristics of package materials. The next step, then, is to go over the data on various materials (1, 5, 10) and package forms (6) with the object of selecting those combinations most likely to meet the requirements. It is presumed that there is available reliable data on the package materials and package forms. Actually, complete data of this kind are not available in many companies and it is usually necessary to select several package combinations on the basis of more or less uncertain information.

Many of the physical, decorative, and preservative properties of package materials can be measured in the laboratory by test methods which have some official approval. For example, the Packaging Institute, the Technical Association of the Pulp and Paper Industry, and the American Society of Testing Materials have developed test procedures based on experience and cooperative work. Some of these methods were not primarily designed for packaging materials, while others are rather loosely drawn and lack reproducibility in some degree. But the chief difficulty is that there are many package requirements for which there are no test methods available at all, except those that have no official basis or proven reliability. Fortunately, the need has been realized and several groups are now engaged in correcting this basic deficiency.

Samples of the selected combinations should be made into packages to approach commercial practice and tolerances. It is highly desirable to test many different and possibly satisfactory packages in the preliminary stages because the number will be continually reduced by a variety of circumstances and limitations. Some reduction will best be made even before laboratory work is begun as a result of discussions with the merchandising group and the production group who, for a variety of reasons, will undoubtedly reject certain of the proposed packages.

The next step should be the laboratory evaluation of the remaining combinations and types to determine their protective qualities and to find out how well they meet the other requirements already outlined. Unfortunately, there is no universal agreement regarding the conditions or manner of running an accelerated package test. In general, the test conditions should be such that typical deterioration occurs at a rate which allows the test to be completed in a time which has some relationship to the desired shelf life (8). For example, tests on a package which is expected to have a shelf life of less than 30 days could safely be acceler-

ated so that laboratory failure would occur in approximately a week. If the shelf life is expected to be about a year, it would be desirable to have laboratory failure occur in from 1 to 2 months. Whatever the conditions and manner of making the test, it should be performed to insure reproducibility so that the data developed can always be compared with previous and future tests. In all tests a few packages should be included which contain a standard material as an absolute basis of comparison, thus affording a means of directly comparing various material combinations

Fig. 2. A controlled humidity cabinet in a packaging laboratory.

and package forms which have been tested at different times. For example, a standard material for the evaluation of moistureproofness of packages might be anhydrous calcium chloride.

The laboratory testing of packages under controlled conditions of temperature and humidity (Fig. 2) is generally accepted as the most satisfactory means of evaluating package protection, interactions between packages and product, and product deterioration. However, there are some who insist upon actual field tests or the translation of laboratory data into days of shelf life in a specific region. At first sight, field tests

would appear to be a practical way to discover actual package performance in a given area of storage and distribution. Such tests have been tried by many companies but have generally been abandoned because of the long time required, the expense of sending samples to many typical areas, and the inconclusive character of the results.

The uncertainties surrounding the interpretation of field tests arise because of short-term abnormalities in weather conditions in the test areas during the test period, and also because test packages are not exposed to a free atmosphere but to one which depends upon many local factors, including the location and the type of the buildings in which the packages are stored. Field tests must therefore be conducted on a very large scale indeed if they are to provide a basis for valid conclusions. On the other hand, laboratory tests furnish an accurate, rapid, and reproducible means of comparing package function, of accumulating valuable data, and of carrying out research on package development. Laboratory data, interpreted in the light of accumulated experience, thus constitute safer grounds for recommendations for packaging a new product. It is often impossible to correlate the results of laboratory tests with those obtained from the usual field tests because the latter are influenced, as already explained, by so many unknown factors. But in the end, of course, conclusions based on laboratory work must stand the test of subsequent general experience in the field. The situation will be familiar to all control chemists who use laboratory tests to measure the utility of a product.

After a first series of laboratory tests, more of the proposed packages will be discarded. A second accelerated test is then made on the remainder, perhaps with some additional packages suggested by the previous results. This will usually bring the laboratory work to a conclusion. If successful, a few packages will have been found that are generally satisfactory in all respects, and the final choice from among these will be made by the merchandising group on the basis of appearance and convenience, and by the production department on the basis of costs and performance on existing packaging machines.

As soon as semiproduction samples are available, a large number of packages and filled shipping cases should be given shipping and rough-handling tests and returned to the laboratory. The laboratory should evaluate these returned samples for physical damage to both product and containers and retest typical packages for possible changes in their preservation quality.

Tentative specifications for all materials and the package should be developed as soon as production standards are known. Obviously, since sample packages may vary considerably from those commercially pro-

duced, the results for handmade packages should not be used as the basis for specifications.

The final package or packages that meet all requirements and conditions should represent some degree of "overpacking"; i.e., they will preserve the product for longer than the normal or mean life expectancy. As experience with commercial shipments is acquired, and as goods returned because of package failures (18) may indicate, it is possible that gradual and tested alterations can be made to lower the package cost.

Conversely, it must be recognized that commercial shipment and returned goods may indicate the need for package improvement. This usually means the package is not performing as planned or that some of the estimates of merchandising and handling factors were too optimistic or based on erroneous reports of the times and conditions of storage, sale, and use. However, there will always be some returned goods attributable to package failure through exposure to unusually adverse conditions or faults in individual packages. The package must be designed to deliver nearly all the goods in satisfactory condition, but it is obviously impossible from an economic standpoint to try to make a package to deliver 100% of the goods in a usable condition.

It has been said many times and should be thoroughly understood that packaging cannot improve an inferior product. Neither can it control the effect of such elemental influences as temperature and normal product aging. If a product is processed under carefully controlled conditions, proper packaging should serve in every possible way to deliver it to its point of use in an acceptable condition. Packaging, therefore, must be considered as a means of maintaining the quality of a product during its shipping, handling, merchandising, and use periods.

Package Types

Cereal products can be packaged in practically all existing package types, although the great majority are packaged in so-called flexible-type containers which include bags and folding cartons of all types and construction. The most popular packages are: bags of cloth, paper, transparent films, foils, or laminations; folding or set-up cartons, with or without liners or overwraps; and fiber cans either composite or all-fiber. There is a very limited use of metal cans and glass jars, mainly for export packaging or for very unstable products.

Bags. A large number of cereal products are packaged in bags of one type or another. The bags vary in capacity from those carrying a few ounces of a household product to 100-lb. units of institutional or industrial feeds or flours. In general, the larger bags are either multi-ply paper, cloth, or cloth-paper combinations. Large units of standard flours and

Causes and Prevention of Typical Forms of Deterioration

The following list was developed to show how various forms of product damage can be reduced by package changes.

Deterioration	Cause	Prevention
Breakage	Rough handling or improper package type	Bags or wrapped trays can allow excessive breakage; change to rigid or carton type package. Use heavier gages of paper board or use trays and dividers.
Caking, lumping	Moisture change	Improved seals and closures. Greater moistureproofness of materials (1, 10). Change of package type.
Staleness	Moisture changes and other causes	Some control may be exercised by proper choice of package type, construction, and materials.
Oxidative rancidity	Oxygen plus fat instability	Use of oxygen-tight packages or ventilation of package to reduce concentration of rancid odors. Use of opaque or light-screening materials.
Loss of aromatic or volatile portions	Diffusion through package materials or seal	Improve seals and closures. Use of package material of low permeability to volatile components.
Infestation (11, 12)	Storage in contaminated space	Complete protection only by use of tight metal or glass containers. Metal foils, well-sealed plastic film, heavy coating or layers of waxes, resins, or asphalt, etc., inclusion of repellents (4), and use of multiple plies can improve package resistance to penetration.

feeds are not easily affected by atmospheric conditions, and the problem is usually one of finding the most economical means of shipping and handling and to provide a container which meets with the requirements of use, such as ease of opening, re-use, identification, and other factors.

Some years ago cotton bags were used almost exclusively for packing of the larger sizes of such products, but reduction of the cost of paper bags and constant improvement in the materials, construction, and means of handling have led to a steady increase in the use of paper at the expense of cotton bags. Either cotton or paper construction will successfully carry many cereal products under normal conditions of storage, distribution, and use in this country. The advantages of the paper bag are its smooth and lint-free surfaces, suitability for multicolor printing, ease of filling by means of built-in valves combined with high-speed packing machinery (Fig. 3), and ease of opening. The paper bag with

pasted bottom or sewn construction can be made to incorporate one or more plies of asphaltic laminations or other protective barriers to increase the resistance to penetration of moisture, or can be made with greaseproof linings to prevent fat-staining of the surface. Because the all-paper multi-ply bag construction lends itself to the incorporation of many kinds of protective materials as one or more of its plies, such bags can be used for the more complex and highly processed cereal products.

Fig. 3. Packing flour in paper bags with built-in valves.

Cloth bags have the advantage of many trips* and re-use for other purposes and for these reasons are in demand in certain markets and for certain products. There is a wide variety of possible cloth-to-cloth or cloth-to-paper laminations, but these greatly increase the cost and reduce the possibility of re-use for nonpackaging purposes. Neither the paper nor the cloth bag is resistant to attack by rodents, but the multi-ply bag is not easily penetrated by many types of insects.

In the smaller sizes of bags there is a great variety of bag construction (gussets, bottoms, or closures, etc.), and the final construction is usually determined by merchandising and use since nearly any material

* Because they are often a source of insect infestation the use of second-hand bags for flour is not favored by the milling industry.

or combinations of materials can be made into any type of construction.

As products become more complex or are packaged in smaller sizes, it often becomes necessary to use a great deal more protection against moisture pickup, staining, etc., and this requires better materials and better closures, seams, and seals. Self-service stores have increased the need for product visibility and multicolor printing. The result is that bags of smaller sizes are found in a great variety of combinations of materials and bag construction. Small bags are very often made of heat-sealing materials with coatings or laminating agents for moistureproofing. Bags, envelopes, or pouches in the smaller sizes (carrying less than 1 lb. of product) are very commonly made from cellophane, cellophane-paper combinations, glassine paper, either plain or laminated, or waxed papers. Cotton bags are now rarely used. In exceptional cases aluminum foil may be used on the exterior or as one of the combined plies. Often the bottom and the side seals of the bag are made by pasting, with the top either double folded and held in position by clips or wire ties or closed by heat-sealing. Usually the exterior surfaces of these small sizes of bags are of coated or highly calendered paper printed in multicolored designs.

In the middle-size range are bags carrying from 1 lb. up to 25 lb. The larger of these will be identical with the 50- or 100-lb. size, that is, a straight paper or cloth bag in either single or multi-ply; sizes approaching 1-lb. capacity will use less decorative and less protective materials than those of still smaller size but will either have more plies or be made of stronger materials.

The final choice of exterior surface ply depends on the quality and amount of the printing and the strength requirements. The choice of the interior ply is dictated by many considerations. For example, it is customary to put white flour in bags which have interior surfaces of blue to enhance the whiteness of the product, and to use a particular type of bag construction which has had long acceptance in the trade. If the product carries any free fat this must be kept from migrating or being absorbed by means of a liner or inner surface having greaseproof qualities. It is a universally accepted principle that greaseproofness in a package must be established at the point of contact with the product.

Premade bags are also very commonly used as liners for folding cartons. This type of carton liner must be distinguished from those formed by high-speed automatic equipment, though the latter may often be used in place of the premade bag.

Folding Cartons. It would be difficult to establish whether bags or folding cartons are most used for packaging of cereals and cereal products, but both are used in very substantial numbers. Folding cartons

protect fragile products from impact and crushing, and certain dense or easy flowing products can be held in better condition by the carton structure. The simpler types of products such as the hot breakfast foods, corn meal, or other ground cereal products, with low moisture pickup and little or no added fat, can be successfully packaged in a folding carton without a liner or loose wrapper.

The gage (thickness) of the paperboard required depends upon the density of the product and the size of the package. As a general rule, folding cartons are not used for more than a few pounds of product. Many sorts of paperboard (14) can be used for folding cartons but, for cereals, grades of better color and strength are usually selected and some attention is paid to odor. The paperboard can be *lined* board, which means that interior and/or exterior surfaces can be made of pulp of improved color, printability, or quality. One of the most important requirements for this type of package is that the carton be carefully die cut and glued to prevent pin holes and mechanical openings in the corners.

Because some cereal products are finely ground or contain fines and all are subject to infestation from outside, it is general practice to use carton liners or exterior wrappers. Liners or "tight" wrappers are particularly well suited to prevent sifting, while either tight or loose wrappers are used to increase resistance to infestation. It is very common practice to "tight wrap" with a printed paper wrapper, which is put on by automatic equipment so that it adheres at all points of contact with the carton. Paper wrappers also provide an improved exterior appearance since a label paper can be printed by more processes and in more detail than most carton surfaces.

With more complex cereal products, requiring more protection against moisture migration, some type of liner or loose overwrap or laminated carton stock, singly or combined, must be used. With cereal products having a low bulk density and a large amount of surface, such as the cold breakfast cereals, the problem is to obtain a high level of resistance to moisture penetration at the lowest possible cost. In general, most moistureproofing of cereal product packages is done by waxed paper formed on automatic machinery into a sealed or semisealed carton liner or overwrapper. The degree of moistureproofness of a lined package depends upon the type of base paper, the amount of wax, and the efficiency in forming the seals and closure of the liner. For products requiring a still greater degree of moistureproofness, wax-laminated and coated liners are used, or liners of two separate sheets. To a lesser extent, moistureproofness is obtained by the use of asphalt or wax to laminate carton board to a paper. Cartons of this type are successfully used but have several disadvantages since the laminating agent is plastic and makes the board

less rigid, particularly in warm weather. Also the laminating agent, by adhering to the cutting dies, tends to reduce production speeds in the manufacture of the carton.

Cartons are also moistureproofed by means of transparent overwraps such as cellophane, lacquered glassine, or certain grades of wax papers. These overwraps are of the loose type as contrasted to the tight wrap or all-over adhered wrapper previously mentioned. A common form of overwrap for plain cartons consists of opaque paper (or paper and metal foil) which has been printed before waxing or lacquering, or a wrapper with all-over ink coverage on cellophane. Such printed overwraps can be applied at high speed from rolls, control of the registration being obtained by an electric eye. Most overwraps of this type are applied by heat sealing their coatings, but if laminated and uncoated materials are used, then adhesives of either an aqueous or a waxy type must be applied to effect the sealing.

Overwraps in general are as efficient and effective as liners or interior bags for moistureproofing and, in some cases, are used as the sole moistureproofing barrier. They have the virtue of protecting the carton from stains by handling and guarantee the purchaser assurance that the carton has not previously been opened (i.e., tamperproofness). Carton overwraps provide an additional barrier to the passage of insects, but it is doubtful if they are of more than slight value for this purpose.

Aluminum foil laminated to paper has been used for products which require an extreme degree of moisture protection. These foil-paper combinations can be used as carton liners, as printed carton overwraps, or the foil may be laminated to the interior or exterior of the carton stock. If the heavier gages of foil are used (about 1/1,000 of an inch) and tight seals and closures are made, the finished structure will afford the maximum protection possible in a flexible-type package against both infestation and moisture change. However, very few cereal products require this degree of protection, while the cost is also against its use.

Care must be taken in the use of transparent overwraps that the carton is made as siftproof as possible; otherwise the product will sift out of the carton and lodge between the carton and the wrapper. This effect is less noticeable if the wrapper is an opaque printed type. Nevertheless, it should be avoided since some products are fairly granular and tend to emboss or even perforate the wrapper. Either effect renders the package less salable.

Composite and All-Fiber Cans. The all-fiber can usually consists of a spiral or convolute wound body, the ends of which are shaped paper cups which have been die-formed into shape. The package is completed by a tightly adherent printed paper label which usually covers the entire

body area and extends over the edges of the caps. The result is a low-cost, strong package, which can be made in many sizes and used for many cereal products, particularly corn meal, rolled oats, bread crumbs, etc. Moistureproofness or greaseproofness can be imparted to the package by the use of certain laminated paperboards for the body, or by the use of special adhesives in making the body, or by a lining ply of greaseproof material, like glassine, aluminum foil, etc. The end caps can be made from similarly laminated or lined materials, and an effective level of moistureproofness thus developed. For protection against insect infestation, this type of container is about equal to the folding carton.

A composite fiber-metal can is made with a body construction similar to the all-fiber can but uses tin plate for either one or both of the ends. With metal ends, friction plugs or similar reclosure means can be used, and the rigidity and strength of the package are greatly increased. Also composite cans can be made much more protective against moisture migration than all-fiber cans since the metal end and the method of clinching it to the body reduce two points of moisture entry.

A special form of the fiber can is the large-size unit called a fiber drum. This container is made by winding heavy paper into a tube using pastes or glues for ply adhesion. There are many means and devices for shaping and securing the bottom and also many types of closure constructions. The final result is a heavy-duty shipping container with a capacity for special or concentrated products up to 200 lb. The cost of the fiber drum and the similar plywood drum is too great in comparison with paper or cloth bags to allow its use for any but higher-cost products.

Metal Cans. All-metal cans are occasionally used for some cereals and cereal products, particularly for extremely long storage or for export shipping where rough handling and severe climatic conditions are encountered. Usually the metal can is not the hermetic or packer can but is the so-called "general line" can which is usually made up without compound or soldering of the ends or of the side seams. These metal cans give complete protection against infestation or attack by rodents. However, it must be remembered that, if the product is not properly processed and free from insects and insect eggs when packed, and if the moisture content is not properly controlled, then spoilage and infestation are likely to occur in the metal can.

Shipping Cases. After being packaged most cereal products are placed in an outer container for shipment. Years ago they were shipped, like most other commodities, in lightweight wooden cases because no other containers were available. With the development of fiberboard it became possible to make containers which were lighter in weight, lower in

cost, and easier to use than wooden boxes. At first solid fiberboard was used but at the present time the overwhelming preference is for the corrugated container. The use of wooden boxes is now restricted to export shipments and military supplies. For the shipment of flour packed in small paper bags (10 lb. and under) multi-wall paper shipping sacks are sometimes used instead of corrugated containers.

Corrugated shipping containers are entirely acceptable for all types of cereal products for domestic use. They are dealt with in Rule 41 of the "Corrugated Freight Classification," a document issued by the Association of American Railroads. The title of Rule 41 is, "Solid or Corrugated Fiber Board Containers" and certain portions of this rule must be complied with or a higher shipping rate is applied as a penalty. It should be noted that the classification tables do not specify the materials or the details of construction but use the Mullen test (Fig. 4) or Cady test as an index of the strength of the container. Cases for most cereal products will not have to hold more than a maximum weight of 65 lb. and can therefore be made of 200-lb. test board.

Corrugated board is made (20) using either Kraft or jute paper for the face with Kraft or straw boards for the corrugating medium. The corrugating itself can be either "A," "B," or "C" flute. These are simple

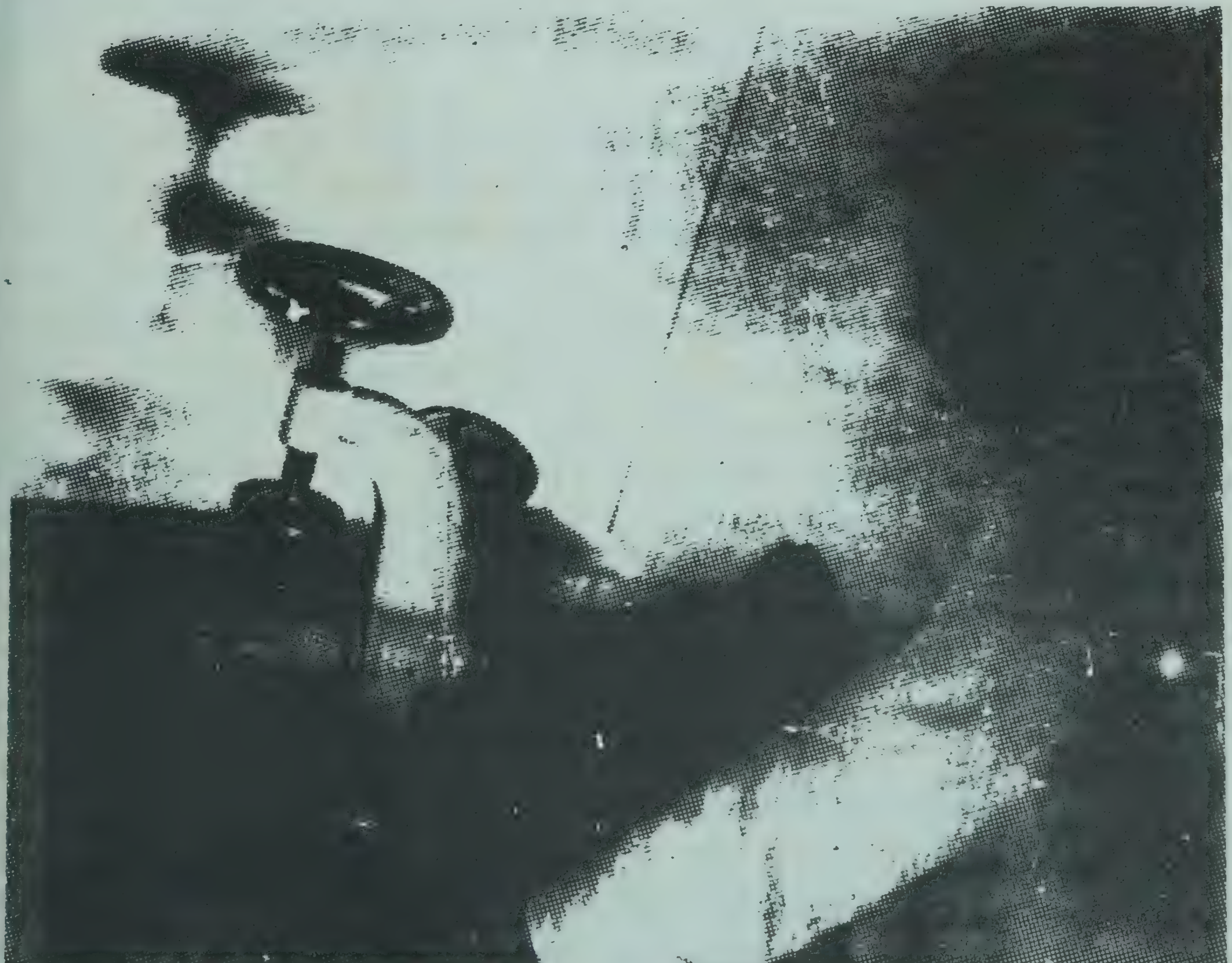

Fig. 4. A Mullen tester for determining the strength of packaging materials.

designations for the number of corrugations per foot and their height. Much of the board used in the cereal industries is made with the "A" flute because this particular construction gives the greatest compression resistance in top to bottom loading of the case.

Several machines are now in use for making compression tests on shipping cases in the laboratory. Tests on empty, sealed cases give a good indication of the general quality of the materials and construction, while results on filled cases supply information as to the maximum safe height of stacking—an important consideration, especially if pallets are used. Many case goods are now handled on pallets for warehousing and transferring to and from trucks and freight cars, even though, at the present time, cereal products are not usually shipped on pallets. As a rule the greatest possible resistance to compression from top to bottom is required because most stacking puts the load in that direction, but, of course, the tests referred to can be used to measure the resistance of the cases to compressive forces in any direction.

The domestic shipping cases covered by Rule 41 are not suitable for most export applications. They can be strengthened by adding steel strapping and by using heavier board, but the recommended practice is to enclose the container in a second case or to slip it into a sleeve and use strapping. For military use or whenever very severe handling must be withstood, a weatherproof solid fiber case or wooden box with strapping is necessary.

Comparative Properties of Packaging Materials. The choice of materials used for the packaging of cereal products in bags and folding cartons and fiber cans can exercise some effect upon the type of deterioration which the product undergoes in storage. For example, there is a very substantial difference in the degree of permeability to organic vapors of cloth and untreated papers on the one hand, and metal foils, plastic films, glassine, and cellophane on the other. Thus, if a product contains aromatic portions which are essential to its character and to make it acceptable for final use, then a packaging material and construction must be selected which will hold the major portion of these aromatics until the time of final use. This not only means a careful selection of the material for its impermeability toward these volatiles, but care in the construction of the package for a minimum of free openings.

Sometimes permeability to organic vapors is a desirable feature. Cereal products which have been subjected to heat or mixed with other materials may become rancid. Experience has shown that the oxidation products responsible for rancid odors do not escape through some packaging materials and the result is a very unpleasant accumulation of

TABLE I

GENERAL PROPERTIES AND USES OF PRINCIPAL CEREAL PACKAGING MATERIALS[a]

Material	Composition	Use	Function	Remarks
Cellophane	A regenerated cellulose film plus coatings	Bags or overwraps, printed or plain	Moistureproofness, heat sealing, greaseproof	A transparent, decorative, and protective film
Plastic films	Made from many resins	Not commonly used for cereals	Dependent upon film and composition	For special purposes
Aluminum foil	Aluminum metal rolled to gages from 0.001 to 0.00035	Usually combined to paper for carton wrapper's, liner's, bags	Decorative, highly moistureproof	Can be printed and coated to make heat sealing
Waxed papers (dry waxed)	Various well-finished papers with small amounts of paraffin wax	Unsealed liners	Not greaseproof, not an effective moisture barrier	A clean material in contact with product
Waxed papers (heavy waxing)	Various well-finished papers with sufficient wax to give intact surface coatings	Plain or printed as carton or product wrappers, liners, or bags	Heat sealable, moistureproof	Can be made semitransparent, or opaque and with good gloss
Coated paper (clay coated)	A soft paper with a casein-bound clay coating on one side	For labels or printed carton wrappers	A base for improving printing quality	Sometimes lacquered to improve finish, to make heat sealing and moistureproof
Coated paper (lacquered)	Usually a special paper, many types of coatings	Opaque, transparent, or printed as carton overwraps or bags. Rarely used as carton liner	Can be moistureproof, heat sealing, decorative	Usually a glassine type paper
Glassine paper	A supercalendered paper of special process and pulps	Bags, liners, laminations, and wrappers	Greaseproof, can be made heat sealing and moistureproof by waxing and laminating	Excellent surface for printing; opaque to semitransparent, odorless
Carton board	Made from many kinds of pulp and processes	Folding cartons, trays, fiber cans, etc.	Stiffness and strength to cartons of all types	Can have many kinds of surfaces, laminations, and coatings
Kraft paper	Kraft or sulphite pulp, bleached or unbleached	Unbleached in multi-wall bags and shipping cases, bleached and printed for single-ply flour or small bags	High strength and durability	Not often coated, waxed, or laminated

[a] See Modern Packaging Encyclopedia 1951, Section 4, and similar sources for more details of the physical and functional properties of packaging materials.

odors by the time the package is opened. By the proper selection of packaging materials, it is possible to allow these undesirable odors to be dissipated through the package walls, without reducing the moistureproofing efficiency of the package in any way. Obviously it is desirable that the product be as stable as possible, but complete inhibition of the development of all forms of rancidity is rarely possible.

In general, cellophane, glassine, parchment paper, certain of the plastic films, and aluminum foil can be considered impervious or nearly so towards organic vapors. On the other hand, papers and paperboard other than those mentioned, whether waxed or not, can be considered as easily permeated by such vapors. This fact is important in the cereal field since an improper choice of packaging material can shorten the shelf life and change the type of failure.

Some of the properties and uses of the principal materials used for packaging cereals are given in Table I. Only a brief summary is given since it would be beyond the scope of this chapter to list and characterize the many packaging materials resulting from laminating, coating, and combining that are commercially available today. More detailed information on any specific material and its suitability for a given requirement can be obtained from various trade associations and manufacturers and from the literature. Such information, as well as the results of special laboratory tests, must be related to the requirements of any particular product. A knowledge of costs is also of great importance in the final selection of the material and package.

Packaging Practices in the Cereal Industries

In the preceding section the various forms of packages used in the cereal industries have been described. We shall now attempt to bring the package and the product together—to consider, in other words, which packages are commonly used for each of the different groups of cereal products. Some repetition of what has already been said will be unavoidable; and, indeed, it seems important to repeat at the outset the statement that similar products can be packaged in a number of different ways, depending upon methods of distribution and the merchandising philosophies of the manufacturers. This complication makes it necessary to limit the discussion to the most generally accepted types and styles of package used for each class of product. Even with that limitation it is not feasible to write detailed specifications for the packaging materials used because different sizes of packages require different weights of board and paper and because the materials themselves are subject to variation.

Cold Breakfast Cereals. Breakfast cereals of the cold type vary greatly in their need for both moistureproofness and physical protection since

they range from products that are crisp and thin to others that are dense and hard. The puffed cereals, including those which have been given a sugar coating, are generally packaged in large, printed cellophane bags. In many cases duplex bags made of two plies of moistureproof cellophane are used. This is done because the resistance to the transmission of water vapor of a single sheet of cellophane is reduced by the printing, while two-ply bags also afford protection against breakage resulting from the dehydration of cellophane in winter storage.

Cold cereals are also packaged in folding cartons of from 1 oz., for individual servings, to about 12-oz. capacity. Because of the highly competitive nature of these products, the package is generally made to appear as large as possible by increasing the size of the front panel with a corresponding reduction in depth. This fact, together with the bulky nature of the product, produces a carton with a very large surface area which must yet have a high degree of moistureproofness. Because of the large surface area of the package and the relatively low cost of its contents, the most economical carton construction compatible with the physical, protective, and printing requirements is essential.

The cartons used are of the folding type with the shortest possible flaps to reduce the amount of board. The carton board is usually news stock or other re-used stocks made on a cylinder machine with a thin surface of a white pulp for printing. These cartons are set up and lined on automatic equipment (Fig. 5) which forms the liner by heat sealing and inserts it into the carton. The liner is usually a 22-lb. basic weight, glassine-type paper carrying about 2 lb. of wax on each surface. After filling, the top of the liner is heat sealed or double folded and crimped. At certain seasons of the year or for shipment to southern markets, the carton may be overwrapped with a loose transparent wrapper of waxed sulphite paper, waxed glassine, or cellophane. Some cereal products of this type are also packaged in a lined but unprinted carton similar to the foregoing but with a loose outer wrap of opaque printed wax paper. Heat sealing of both liner and wrapper produces the greatest possible protection against moisture penetration and insect infestation that is obtainable with an all-paper package.

Denser and less moisture-sensitive cold cereals are sold in similar packages except that either a liner or overwrap is used, but usually not both. A cellophane overwrap may be applied but this is rather uncommon because of the added cost and the danger of accumulation of odors resulting from oxidation.

Hot Cereals, etc. Hot cereals are always free-flowing, relatively dense products which have not been greatly altered in processing and are not particularly sensitive to moisture changes. Most products of this type

Fig. 5. Machine for making lined packages.

are packaged in a heavy-gage folding carton (up to 0.030 in. thick) without a liner and with a printed paper wrapper on the outside. The paperboard is usually of better grade than that used for cold cereals and may have an interior surface of a semibleached or bleached pulp to improve its appearance and to reduce interaction between the product and the re-used pulps of the body stock. The printed paper wrapper is firmly applied to the carton surface with an all-over adhesive and is designed to prevent sifting of the product and to reduce the possibility of infestation. A similar package construction is used for corn starch, corn meal, and other products having similar physical properties and preservation requirements.

Hot cereals, corn meal, cracker crumbs, etc., are sometimes packaged in all-fiber cans, apparently because the consumer has long been accustomed to accepting certain brands in this type of container. These packages are usually made from spirally wound paper tubes of more than one ply, the adhesive being a vegetable paste. The ends are cup-shaped and are formed by stamping a heavy-gage paperboard which has been steamed or moistened before the forming operations. The formed ends are slipped over the fiber body and are allowed to dry in position, which shrinks them firmly to the body. The filled package is labeled with a paper label which comes up over the end caps and is

all-over glued. This gives a strong, non-sifting, low-cost package with some resistance to infestation. It can be made with varying degrees of moistureproofness depending on the material used for the inner ply, the label, or the laminating agent.

Macaroni Products. Macaroni, spaghetti, and similar products are nearly always packaged in a particular style of folding carton which has been used so long that it is always associated with these products. The package, relatively long as compared with its cross section, is a lock-end type carton with a tucked top. Locking is done by inserting special flaps into slots on the narrow end; the tuck top extends the full length of the package. The carton, made of low-cost stock with a good printing surface on the exterior, is usually set up with a piece of lining paper which folds in with end tucks to form what is known in the trade as a Peters-style carton and liner. After the product is loaded, the ends of the liner are folded over and the carton top tucked into position. If the carton is unprinted, then a loose printed paper wrapper is used. The liner is made of any good grade of white paper or glassine, usually without any wax or impregnation. The resulting package is not moistureproof but gives some physical protection to the product, is low in cost, and adaptable to automatic or semiautomatic packing operations.

Bread Flours. Consumer packages of bread flour vary from a few pounds to a hundred pounds in weight. This product does not require moistureproofness, the principal requirement being a strong, attractive bag which is resistant to sifting and easy infestation. Paper bags used for flour vary little in character from one size to another, but more plies or greater thickness of ply must be used as size is increased. Thus 5-lb. bags are made of paper of about 70-lb. weight and 10-lb. bags from 80-lb. paper; for bags holding 25 lb. of flour, paper of about 125-lb. basic weight is required. In still larger sizes more than one ply of paper may be used, depending upon the paper stock and its weight.

The paper is usually manufactured from rope or jute stock or from long-fiber, high-strength Kraft. It must be soft and relatively porous to air so that less flour will puff out when the bags are filled on high speed, automatic machines. For smaller bags the paper is sometimes embossed to increase its softness and improve its appearance, while the exterior surface is always treated with a white pigment or pulp to give a better surface for printing. As mentioned previously, the interior surface may be colored blue to enhance the whiteness of the flour.

The construction of paper bags varies according to the type of machine on which they are made and the way they are to be filled and closed. There are several different types of closures: a simple wire or string tie, a sewn top, a folded and pasted-down top which, when care-

fully opened, provides a pouring means, and a top turned down several times and pasted against the body of the bag.

Cake Flours. Cake flours are usually packaged in folding cartons holding 2 or 3 lbs. The carton is about a 30-point (0.030-in.) board made from a good grade of re-used pulps. To minimize the danger of contamination, the interior surface of the board is often made of a still better grade of pulp. The filled and sealed cartons are overwrapped with a tight-wrapped, printed paper label. There may be scored and preperforated lines on the carton and wrapper to facilitate opening and reclosure. The package is not moistureproof, but is strong and stiff enough not to be bulged by the weight of the contents, and has reasonable resistance to infestation.

Cake Mixes. The packaging of cake mixtures is complicated by the inclusion of leavening agents, sugar, flavor, and coloring materials which may be hygroscopic and moisture-sensitive in varying degrees. The package often consists of a folding carton of about a 24-point board with a machine-formed liner of laminated glassine or an inserted, laminated glassine bag. After the lined carton is filled, the liner or bag closure is heat-sealed or well folded and crimped, the flaps are sealed, and the carton is overwrapped with a printed, tight wrapper. There is no particular need for a high quality board since the product is always placed in laminated glassine to prevent any contact of product with the carton wall. The laminated glassine also gives protection against the loss of volatile flavorings, prevents fat penetration, and provides excellent moistureproofness. Aluminum foil, less than 0.001 in. thick, laminated to paper makes a very attractive wrapper and, when properly applied, greatly improves the moisture resistance of the package and also its resistance to infestation. Another satisfactory package consists of a lined and printed carton with a moistureproof cellophane overwrap.

Cookies and Crackers. Cookies and crackers include an extremely wide range of products from hard, dense types having little moisture sensitivity, to complex products carrying oils and fats and having various surface coatings or fillings, usually of a sugary type. The simpler and more stable products such as graham crackers, soda crackers, etc., can be packaged in a Peters-type carton (see Macaroni Products), using a liner of plain or waxed glassine and a loose, printed paper overwrap. The liners in these packages are left unsealed to allow the escape of any odors resulting from the oxidation of fats.

Many cookies carrying a high sugar content and requiring moistureproofness are packaged in a folding carton with full flaps and a tuck top. The liner, machine-formed or of the inserted bag type, is made from waxed glassine, laminated glassine, wax sulphite papers, or, more

rarely, moistureproof cellophane. The carton may be printed, but if not, then a printed overwrap is used which is often an opaque waxed wrapper or cellophane sealed by heat. Other packages for sweet cookies consist of a paperboard tray or stiffener which is slipped into a cellophane bag. The problem here is to prevent undue breakage. Because of their irregular shape and brittleness, cookies of this sort must often be packed by hand or by semiautomatic means. Other problems in the packaging of fancy cookies are to prevent undue staining or penetration of the packages by fats and to provide a high level of protection against moisture absorption. Both must be done without unduly increasing the cost or unduly complicating the construction of the packages. Many companies use folding cartons for larger packages and transparent cellophane bags for the smaller ones. If the cellophane is unprinted, paper labels may be applied by heat sealing or printed paper may be stapled or sealed over the bag closure. Cellophane is a very popular material for sweet cookies because product visibility is considered helpful in merchandising.

In this same general class are many complex products sold as snack or cocktail items. These may be fried, puffed, or surface treated with flavoring ingredients. Many of them are packaged in small sizes in printed, laminated glassine bags, duplex cellophane, or a combination of cellophane and laminated glassine. Sometimes a colored or tinted ply is used to enhance the color of the product or in the belief that the color screen will reduce the rate of rancidity development. Such color screens are of doubtful value since light is not the only cause of rancidity, and the packages are rarely exposed to direct sunlight in normal distribution. The bag should be well made and sealed to give, though for short periods only, protection against rancidity and infestation. No package can do more than this for such unstable products. Even in a completely moistureproof package rancidity and staling cannot be long delayed. A decorative bag that will give a reasonable degree of protection at low cost is therefore used. To prevent products becoming unattractive or unsalable there must be close control of stocks and policing of sales outlets.

Bread. Bread is usually packaged in heat-sealed wrappers of printed waxed paper (23-lb. paper waxed to 35 lb. per ream), though a special grade of moistureproof cellophane is popular for special loaves. The necessity for having the most economical wrapper limits the use of cellophane for white bread. The wrapper should not be too moistureproof as this may induce mold growth on the bread surface. Much work has been done to develop wrappers carrying mold-inhibiting additives, but so far, effective compounds have not been put into commercial use because

of their possible toxicity. Bread is another example of a product that must have a rapid turnover to reduce the volume of returned goods. The wrapper prevents excessive moisture losses, carries the maker's trademark, and keeps the product clean in handling. All wrappers should have good overlaps and seal area to prevent their coming off in handling. Rolls and similar baked goods can be packaged like bread, but often trays or open-sided cartons are used with the wrapper on the outside.

Cakes. There are many kinds of cakes, and these vary widely in stability and durability. Firm cakes can be packaged like bread or rolls, while those having icings or soft structures require a rigid carton to prevent disfiguration. Fancy and holiday cakes are often packaged in lithographed metal cans, plastic boxes, or in set-up boxes with cellophane, foil, or other decorated films as overwraps. Similar packaging is used for other baked goods having fillings, top dressings, and delicate structures. The problem is to prevent physical damage and too much moisture loss. Long storage is never involved and the usual cost limitations often do not apply. Too much moistureproofness produces sogginess and accelerates mold growth. If icings are used, very little or no moistureproofness is desirable.

Trends and Developments

The packaging of cereals and cereal products has been affected and will continue to be affected by certain general trends in packaging methods and package construction. The most important of these trends are: the use of more decoration and transparency, the simplification of package construction, the adoption of unit packages (single servings), the production of packages by automatic means, and increased use of heat sealing. Developments which are of particular interest in the field of cereal packaging are: improvements in insect and rodent resistance (4, 7), and the use of antimycotic materials.

The multiplication of retail outlets of the self-service type has greatly increased the importance of the package as a merchandising tool. These modern methods of distribution have made it essential to have a package of the most attractive appearance if the customer's favor is to be won. Thus we find present-day packages distinguished by good art work, striking colors, and glossy surfaces. Product identification is often accomplished by process printing, so that the package may carry an attractive and authentic reproduction of the product. This requires the use of more complex printing processes and the selection of package materials with improved surfaces. In some classes of products, inspection as well as identification is made possible by using transparent material

for all or part of the package, though this is not always feasible because of the need for protection or some other requirement.

Consumer research has indicated that the user desires a package which is convenient to handle and open, and which is adapted to the way in which the product is used. This requirement can best be met by keeping the construction as simple as possible, by the use of easy means for opening and reclosing and, in some cases, by the addition of opening or pouring devices, etc. It is not easy to satisfy these requirements and at the same time meet the increasing need for improved preservation and low cost.

For many years there has been a growing demand for packages carrying sufficient product for a single use, or so-called "unit packages." This trend has resulted in a greatly increased number of single-serving packages for cold breakfast cereals. A unit package must be carefully designed and automatically produced because, with these smaller packages, preservation becomes more difficult and more packaging material is required.

The use of automatic machinery for making packages and for filling and closing them has been brought about by the great increase in the production of packaged goods and by steadily rising labor costs. Developments in this field have led to the production of certain basic types of package-making machinery which are modified for particular uses. There are few special problems in adapting machinery to handle most cereal products. However, some cereal products, such as cookies and crackers, because of their irregular shape and brittleness, require special machines for the filling operation and although many problems have been solved there is still much work to be done in this field. The use of automatic machinery is made easier by the simplification of packages and the use of heat sealing, since these measures reduce the number of machines required or allow higher production rates to be attained.

Besides increasing the speed and the simplicity of automatic machines, the use of heat-sealing materials has been an important factor in improving the preservative functions of packages, and of making them more attractive and convenient in use. New package materials are continually being produced and many of them come from the plastics industry. These materials, whether they are films or resins used in coatings or adhesives, have great promise in the manufacture of flexible packages which, by heat sealing, can be made hermetic and so permit the use of inert gases or vacuum, or even the packaging of sterile products.

The distribution of cereal products will particularly benefit from the work being done to improve the resistance of packages to insect and

rodent attack and to incorporate antimycotic agents into package materials. The main problem here is to provide effective levels of resistance or activity without contamination of the product. This problem has not been solved, but because of its economic importance and the intensity of the work being done, progress may be confidently expected.

With the growing complexity of products and the trend towards smaller selling units, improved and novel functional properties are demanded of the package. This trend has been accelerated by the centralization of facilities for the manufacture of cereal products, which results in a longer storage time and increased handling. As each new package material comes on the market, it is immediately evaluated and, if it has unusual properties or can effect economies, it may be expected to solve some existing problem or make possible an improved package for some product. The annual dollar volume of packaging materials is so large that a great deal of research and development work is being done by the many companies who are already in this business or who are attracted by its volume and potentialities. This results in a continuous flow of new resins, films, coatings, processes, and combinations of materials which must be evaluated before they can find their proper place in packaging. The package user who does not continually evaluate new materials, constructions, and processes, by the use of ever more scientific methods, and who is not aware of the trends and the needs of his customers, may rapidly fall behind under today's competitive conditions.

Packaging is now accepted as a vital and necessary part of the storage, handling, display, and preservation of the goods in our present economy. The package must accomplish all its functions at the lowest possible cost. The continuing need for improving packages and reducing their costs, coupled with the rapid progress in the packaging field, makes it imperative for every large company to insure its future by organizing and staffing an integrated packaging section. The company that does not keep pace with package developments will find itself in economic difficulties regardless of its skill as a producer or the quality of its product.

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